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THE RADIOLOGICAL IMPLICATIONS OF USING PORT HOPE SEWAGE SLUDGE ON FARM LAND

by

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Research report

THE RADIOLOGICAL IMPLICATIONS OF USING PORT HOPE SEWAGE SLUDGE ON FARM LAND

ABSTRACT

For several years, sewage sludges from the Port Hope Pollution Control Plant were used as agricultural fertilizer. In 1985, the sludges were found to contain uranium, originating primarily from a uranium refinery, and, in the absence of guidelines for land application of sludges containing uranium, landspreading was suspended. This research project was undertaken to determine the levels of uranium and its decay products in Port Hope sludge, compare these with levels found in other sewage sludges, determine whether any build-up of uranium has occurred in soils fertilized with Port Hope sludge, and calculate the dose to the most highly exposed group (farmers).

Uranium concentrations in Port Hope sludge averaged 6 ppm (wet weight), and were higher than in other sludges sampled. Levels of uranium 238 decay products were slightly elevated in the Port Hope sludge relative to other sludges. In soil samples taken from farms having a history of high sludge application rates, uranium concentrations were slightly higher than in the soil samples from farms considered as controls. If sludge is applied at the rate allowed by the provincial sludge utilization guidelines, it is estimated that the concentration of uranium in surface soil, per application, would be 0.85 ppm. The individual effective dose equivalent attributed to sludge used at the rate allowed in the sludge guidelines is 0.00059 $mSv.a^{-1}$, for soils treated once, through internal and external exposure pathways. If sludge is applied for 50 years at this rate, then, at that time, the effective dose equivalent received by a hypothetical farmer living on the farm and consuming crops from these fields is estimated to be approximately 0.0056 $mSv.a^{-1}$. By comparison, this dose is 0.3% of the natural background radiation dose of approximately 2 mSv received annually by members of the general public, a dose considered to be insignificant by national and international authorities.

The estimated rate of ingestion of uranium from the consumption of crops grown on fields fertilized with Port Hope sludge is well below the level that would be toxic to humans. Similarly, the concentration of uranium in soils treated with Port Hope sludge is much lower than the level considered likely to be toxic to plants.

RÉSUMÉ

Depuis plusieurs années, les boues d'égout de l'usine d'épuration des eaux usées de Port Hope étaient utilisées comme engrais agricole. En 1985, on a découvert que ces boues contenaient de l'uranium qui provenait en majeure partie d'une raffinerie d'uranium. Faute de lignes directrices précises sur l'utilisation des boues contenant de l'uranium sur le sol, l'épandage a été suspendu. Le présent projet de recherche a donc été entrepris pour déterminer la quantité d'uranium et de ses produits de désintégration dans les boues de Port Hope, la comparer à la teneur de d'autres boues d'égout, déterminer si l'uranium s'est accumulé dans les terres fertilisées par les boues de Port Hope et calculer la dose du groupe le plus exposé, soit les agriculteurs.

La concentration moyenne d'uranium dans les boues de Port Hope atteignait 6 ppm (poids frais) et était supérieure à la teneur en uranium des autres échantillons de boues. La concentration des produits de désintégration de l'uranium 238 y était aussi un peu plus élevée. Dans les échantillons de sol des champs où l'on avait épandu beaucoup de boues précédemment, la concentration d'uranium était légèrement plus élevée que dans les échantillons de sol de champs repères. Si les boues étaient épandues selon le débit autorisé par les lignes directrices provinciales pertinentes, on estime que la concentration d'uranium dans les sols de surface serait de 0,85 ppm par épandage. Pour les terres traitées une seule fois, l'équivalent de dose effectif dû aux boues épandues au débit autorisé serait de 0,00059 $mSv.a^{-1}$, compte tenu des voies d'acheminement internes et externes. Pour un débit d'épandage semblable étalé sur 50 ans à ce rythme, on estime que l'équivalent de dose effectif de tout agriculteur vivant sur sa ferme et consommant le produit des récoltes de ses champs, au bout de cette période, serait d'environ 0,0056 $mSv.a^{-1}$. Par comparaison, cette dose correspond à 0,3 pour 100 de la dose d'environ 2 mSv due au fond naturel de rayonnement et reçue annuellememnt par les membres du grand public, soit une dose qui est considérée comme peu importante par les autorités nationales et internationales.

Le taux estimé d'ingestion d'uranium par suite de la consommation des récoltes cultivées dans les champs fertilisés avec les boues de Port Hope se situe à un niveau bien inférieur à celui qui serait toxique pour les humains. De même, la concentration d'uranium dans les sols engraissés avec les boues de Port Hope est très inférieure au niveau qui pourrait être toxique pour les plantes.

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EXECUTIVE SUMMARY

The Atomic Energy Control Board (AECB) initiated this research to evaluate the radiological implications of landspreading of Port Hope sewage sludge. Until 1985, sewage sludges from the Port Hope Water Pollution Control Plant (WPCP) had been used as agricultural fertilizers, under guideline limits set by the Ontario Ministries of Agriculture and Food, Environment, and Health. A sampling program carried out in 1985 showed these sludges to contain uranium, and subsequent investigations identified the principal source as the Eldorado Resources Limited uranium refinery. In the absence of guidelines for the land application of sludges containing uranium, landspreading activities were suspended by the Ontario Ministry of the Environment and sludge stockpiled pending an assessment of the agricultural and public health consequences of this practice. In addressing the radiological implications of landspreading of Port Hope sludge, the AECB sponsored this project to verify the levels of uranium and its decay products in the stockpiled and fresh Port Hope sludge, compare these with levels found in sludges from other municipalities, determine if any discernible build-up of uranium has occurred in soils previously fertilized with Port Hope sludge, and to calculate the radiological dose equivalent to the most highly exposed group as a result of sludge spreading practices.

While addressing the radiological concerns of the AECB, it became evident to the study team that other considerations relating to the application of Port Hope sludge are also of importance and, in the interest of compiling a comprehensive assessment, are also addressed in this report. These ancillary considerations relate to the potential chemical toxicity of uranium to crops and to man.

Uranium concentrations in the Port Hope sludges averaged about 6 ppm on a wet weight basis, and were higher than the 0.25 ppm or less in other WPCP sludges. The uranium concentration in Port Hope sludge is expected to fall in response to reductions in uranium losses recently achieved by the refinery. Levels of U-238 decay products were only slightly elevated in the Port Hope sludges relative to other sludges. In soils from farms having a history of very high application rates of Port Hope sewage sludge, uranium concentrations ranged between 1.9 and 12.9 ppm, although only one sample showed concentrations above 3.1 ppm. Concentrations in control soils were 1.0 to 2.3 ppm, with the lowest concentrations occurring where inorganic fertilizers have probably never been applied. Measured concentrations in treated fields could be roughly predicted from

sludge application records. Differences between predicted and observed concentrations in some cases implied some weathering loss of the uranium added through sludge application.

Uranium and U-238 decay products occurred at much lower concentrations in Port Hope sewage sludge than in typical inorganic phosphate fertilizers. However, concentrations would be slightly higher in soils fertilized with Port Hope sewage sludge than with a typical phosphate fertilizer due to the large volumes of sludge required for effective fertilization. Although there are no guidelines for radionuclide content in sewage sludge, "Ontario's Guidelines for Sewage Sludge Utilization on Agricultural Lands" stipulate that the sludge application rate should be such that the maximum quantity of ammonium plus nitrate nitrogen added to farmland through sludge application over any five-year period should not exceed 135 kg per hectare. If Port Hope sludge is utilized as fertilizer on agricultural land according to these provincial guidelines, the maximum concentration of radionuclides added over a five-year period would be 0.85 ppm of uranium and 0.1 to 0.4 $mBq \cdot g^{-1}$ each of Th-230, Ra-226, Pb-210 and Po-210. These are less than typical background concentrations of about 2 ppm for natural uranium and 25 $mBq \cdot g^{-1}$ for members of the U-238 decay series.

Edible plant tissues, sampled from sludge-treated fields and stockpiled Port Hope sludges, generally had uranium concentrations that were below the 0.2 ppm dry weight detection limit, including tomatoes growing on undiluted sludge. Leaves and stems had slightly higher uranium concentrations, while roots typically showed the highest uranium concentrations (up to 4 ppm dry weight). The average soil-to-plant transfer coefficient for uranium was 0.0063 for all tissues (fresh weight plant-dry weight soil basis). This coefficient was used to estimate uranium ingestion rates in the radiological assessment.

The effective dose equivalent attributed to sludge use received by a hypothetical farmer fertilizing his fields with Port Hope sewage sludge at the rate prescribed by provincial sludge utilization guidelines and consuming crops from these same fields is estimated at 0.00059 $mSv \cdot yr^{-1}$ for soils treated over five years, assuming exposure through radionucide inhalation in dust and ingestion of crops, as well as exposure to gamma radiation from airborne dust and the surface soil. If sludge is used at the prescribed rate over 50 years, at that time the farmer would be receiving about 0.0056 $mSv \cdot yr^{-1}$. About 91% of the total dose is attributed to uranium, and the balance to Th-230 and its decay

products. Most of the total dose would be received through ingestion of crops grown on these fields. For comparison purposes, 0.0056 mSv is 0.3% of the natural background radiation dose of approximately 2 mSv received annually by members of the Canadian general public, and is trivial based on national and international criteria.

In conclusion, utilization of Port Hope sewage sludge on soils at the rates prescribed in the provincial sludge utilization guidelines will not pose a significant radiological risk to humans.

The intake of uranium from consumption of crops grown on fields fertilized with Port Hope sludge would be low relative to quantities identified by Health and Welfare Canada as safe from a chemical toxicity perspective. Therefore, it is concluded that the ingestion of uranium resulting from sludge application would result in no chemical hazard.

The maximum concentration of uranium in soil that should not elicit chemical toxic effects in crops is thought to be 10 ppm, based on a single study on wheat grown in soils treated with uranyl nitrate. The uranium in Port Hope sludge is probably less bioavailable than soluble uranyl nitrate; thus, a safe upper limit for uranium in sludge-treated soils may be higher. About 50 years of sludge application at the prescribed rate would be required to bring soil uranium concentrations to 10 ppm, assuming no weathering losses. Uranium would present a chemical danger to plants long before posing any radiological or chemical danger to man. Accumulations of other trace metals occur from regular application of sewage sludge from any WPCP. The time required to reach maximum acceptable concentrations of these metals, based on the provincial guidelines, is similar to that for uranium at concentrations found in Port Hope sludge. Accordingly, uranium in Port Hope sewage sludge would appear to pose no greater concern in terms of plant toxicity than do other metals found in sewage sludges at the concentration limits (nitrogen to metal ratios) identified in the sludge utilization guidelines.

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1.0 INTRODUCTION

1.1 Background

The Town of Port Hope operates a water pollution control plant (WPCP) for the treatment of sewage from Port Hope prior to discharge to Lake Ontario. The WPCP has a capacity of two million gallons (9,092 m^3) per day, and uses both a conventional activated sludge process and a high rate aerobic treatment process for the oxidation and removal of organic matter. The average daily flow in 1986 was 1.669 million gallons (A. Walsh, Port Hope WPCP, pers. comm.). This has since been reduced to about one million gallons per day through diversion of cooling water. Annual sludge production in 1986 was 396,625 gallons (1,801 m^3) of anaerobic sludge and 59,250 gallons (269 m^3) of aerobic sludge.

About 1.25 million cubic metres of wet sewage sludge, or close to 20% of the 6.5 to 7 million cubic metres produced annually in Ontario, are used as fertilizer on agricultural land (F. Iliffe, Ontario Ministry of the Environment, pers. comm.). Sludge application guidelines have been established by the Ontario Ministry of Agriculture and Food, Ministry of the Environment and Ministry of Health (MAF/MOE/ MOH) in "Ontario's Guidelines for Sewage Sludge Utilization on Agricultural Lands" (MAF/MOE/MOH, 1986). The provincial guidelines stipulate that the sludge application rate should be such that the maximum quantity of ammonium plus nitrate nitrogen added to farmland through the sludge over any five-year period should not exceed 135 kg per hectare. While the guidelines establish concentration limits for several potentially toxic metals in sewage sludge applied to farmland, based on nitrogen to metal ratios, no concentration limits are given for uranium and other radionuclides.

Until September 1985, Port Hope sewage sludges were applied to regional farmland as fertilizer. Aerobic sludge, when applied, was typically blended with equal volumes of anaerobic sludge before landspreading in order to maintain adequate inorganic nitrogen levels for fertilization. Anaerobic sludge was used in both blended and unblended forms. In September 1985, relatively high uranium concentrations were discovered in the Port Hope sewage sludges, and landspreading of the sludges was ordered discontinued until an evaluation of the environmental implications of the practice was carried out. All sludges generated since September 1985 have been dewatered in drying beds and stockpiled around the WPCP property. Sludges generated prior to September 1985 were

frequently dried and stockpiled over winter months when landspreading was not carried out. Piles of dried sludge dating back to the winter of 1981/82 are dispersed around the Port Hope WPCP. Historically, local residents were encouraged to remove this dried sludge for household garden application.

An Ad Hoc Subcommittee of the Council of the Town of Port Hope was established in November 1986 to determine the sources of uranium in the municipal sewage. In response, two studies were carried out. The Low-Level Radioactive Waste Management Office (LLRWMO) of Atomic Energy of Canada Limited, which has been designated by the federal government as the agency responsible for cleanup and disposal of historic radioactive wastes[1], collected a series of sewage samples from locations influenced by the two industrial processors of uranium in Port Hope, from locations close to historic waste locations and other key sites in the sewer system, as well as sites within the WPCP (Pollock, 1987). In a second study, a series of samples were collected within the WPCP and upstream to determine the mass balance and partitioning of uranium in raw sewage, effluents and sludges (Brown, 1987). Both studies were carried out in December 1986 and January 1987. Neither study evaluated sources or concentrations of U-238 decay products in the Port Hope sewage system.

From these two studies, several conclusions were drawn. The study by the LLRWMO showed that most of the uranium enters the sewer through the Hayward Street line which drains the Eldorado Resources Limited (ERL) uranium refining site. Other contributing sources were minor, and no contribution could be distinguished from historic waste sites. Daily loadings of uranium to the WPCP in this study were estimated to range between 61 and 231 g (average of 132 g).

In the second study, the average daily loading of uranium to the WPCP was 161 g, based on nine samples collected from each of two sewer trunks. Of this total, 94% came from the Mill Street main downstream of ERL. An average of 100 g per day was found to be discharged with the WPCP effluent. The difference of 61 g per day is retained in sewage

1 Historic wastes are those managed in the past in a manner no longer considered acceptable, but for which the original producer can no longer be reasonably held responsible.

sludges. From measurements of solids removal efficiency and uranium concentrations in sludges, a daily retention of 41 g of uranium was implied. Given the uncertainties in the measurements, the agreement between the 41 g and 61 g values is reasonable for uranium retention.

Concentrations of uranium in Port Hope sludges have been determined in these studies, and have been routinely measured by the Ontario Ministry of the Environment (MOE) in their sludge monitoring program. These data show uranium concentrations of typically 2 to 10 ppm in wet sludge (mean of about 6 ppm) and about 150 to 450 ppm in dry sludges (mean of about 260 ppm) (Table A1.1, Appendix 1). Limited data are also available on activities of uranium decay products (principally Ra-226) in Port Hope sludges (Table A1.2, Appendix 1).

ERL has subsequently taken steps to reduce its uranium loadings to the Port Hope sewage system. In July 1987, ERL's laundry water and floor washing water were diverted from the sewer to an evaporation system. Residue from the evaporator is disposed of in the Port Granby waste management facility. As a result, the daily uranium loading to the sewer has been reduced by about one-third, to an estimated 100 g per day (H. Carisse, ERL, pers. comm.). ERL is also endeavouring to divert site stormwater drainage from the sewer, which should result in further reductions in the uranium loading. Given a lifetime in the order of weeks to months for sludges in the Port Hope WPCP, these reductions should not be expected to result in immediate reductions in uranium levels in digested sludges.

Upon finding high uranium concentrations in Port Hope sewage sludges, the Ontario Ministry of the Environment (MOE) initiated a program to survey agricultural soils that had been fertilized with the contaminated sludges. Results of a preliminary survey conducted in 1986 and a more extensive survey in 1987 by the Peterborough District Office of the MOE are presented in Table A1.3 (Appendix 1). In most cases, soil uranium levels were below 3 ppm, but relatively high levels (up to 22 ppm) were found in soils at one farm. Levels of Ra-226 in soils at this farm were similar to, or only slightly greater than, levels identified in control samples.

In April 1986, D.L. McLaughlin of the MOE investigated the concentrations of uranium and other metals in soils and crops in a Port Hope herb garden liberally amended with

dried sewage sludge from the WPCP (McLaughlin, 1986a). As shown in Table A1.4 (Appendix 1), uranium concentrations in the garden soil ranged between 2.3 and 23 ppm, while uranium in plant foliage ranged between 0.08 and 0.34 ppm. In comparison, soil uranium concentrations were below 2 ppm in the control garden, while plant foliage concentrations were 0.02 to 0.05 ppm. It was concluded in the report that uranium at these concentrations posed no chemical or radiological hazard to consumers.

1.2 Objectives

Beak Consultants Limited (BEAK) was contracted by the Atomic Energy Control Board to:

- verify the levels of uranium and decay products in stockpiled and fresh Port Hope sludges;
- compare these levels with levels found in sludges from other regional municipalities;
- determine if any discernible build-up of uranium has occurred in soils and crops fertilized with Port Hope sludges;
- evaluate the rate of uranium accumulation in soils as it relates to normal sludge application practices; and
- evaluate the potential radiological risk to individuals exposed to soils and crops fertilized with Port Hope sewage sludge.

In addition to addressing these AECB study objectives, other data believed relevant to evaluating the overall safety of landspreading of Port Hope sewage sludge were also compiled and evaluated by BEAK. These evaluations relate to the chemical toxicity of uranium to crops and man.

2.0 METHODS

Fresh sludge samples were collected on three occasions at the Port Hope WPCP and at three other plants - Cobourg, Whitby-Pringle Creek and Whitby-Corbett Creek. Samples were also collected twice at the Port Darlington (Bowmanville) WPCP. These plants service populations ranging between 2,500 and 17,500. Sludges from all WPCP's other than Port Hope are used as agricultural fertilizer, although Pringle Creek sludge is blended (diluted) with Corbett Creek sludge prior to landspreading, because cadmium concentrations in the Pringle Creek sludge exceed levels permitted in the Ontario "Guidelines for Sewage Sludge Utilization on Agricultural Lands" (MAF/MOE/MOH, 1986). Sludges were collected on 30 July, 08 August and 26 August 1987.

At Port Hope, sludges were collected from four sources within the plant - anaerobic raw and digested sludge, and aerobic raw (also called waste) and digested sludge. These were grab samples collected with the assistance of Mr. A. Walsh. Undigested sludge has been in the plant for a period of days, and was sampled to determine whether the effects of the annual plant shutdown at ERL in July would be reflected in sludge uranium levels. The digested sludges reside about one month (anaerobic) to three months (aerobic) in the WPCP, and thus should be less sensitive to daily or weekly fluctuations in uranium loadings to the sewer. Older, partially dry to dry digested sludges stored since 1981/82, 1983/84, 1985, 1985/86, October 1986 and 1987 at the Port Hope WPCP site were collected on one occasion as single composites of several grab samples from each source. Sludges sampled from all other WPCP's were anaerobically digested; none of these other plants use an aerobic digestion process.

The agricultural survey was carried out with the assistance of the Peterborough District of the MOE, who had compiled historic records of sludge additions for several farms that had used Port Hope sludges and had initiated a soil quality monitoring program to measure soil uranium, Ra-226 and metal concentrations. In many cases, records of the precise areas fertilized and sludge volumes applied were sketchy (Table A1.3). The farms sampled in this survey and in the MOE survey are identified in this report by numeric code to respect the confidentiality of the owners. Farm owners and locations have been provided to the AECB under separate cover. Four farms that had reasonably good records and had received large quantities of sludges were selected for this study. These farms are numbered 6, 14, 15 and 21, and correspond with farms bearing the same

numbers in the MOE survey (Table A1.3). Rates of sludge addition to these four farms were reported as 3.6 to 27 times the rates prescribed by the MOE. Both sludge-treated fields and control fields or woodlots were sampled.

Soil samples were collected as composites, consisting of several cores collected from a 15-cm plough depth. Grab samples from sludge-treated fields were collected at regular intervals dispersed over the entire treated area. Control samples were also collected as composites of several grabs from the 15 cm plough depth. Samples were composited in a bucket, mixed, and samples of about 100 g placed in clean polyethylene bags. Field staff from both the MOE and BEAK participated in soil sample collection, to ensure that sampling procedures in this study were consistent with those in the more extensive MOE soil sampling program. Soils from two of the four sampling sites were split for comparative analysis by the MOE and BEAK.

Plant samples were collected from the same locations as the soil samples, and consisted similarly of composites of several grab samples. Plant samples were also collected from dried sludge piles to provide an indication of uranium uptake under maximum uranium concentrations. Tissues collected included shoots, fruit, grain and roots, although not all tissues were collected at every location. Priority was given to the collection of edible plant parts. The 1985/86 sludge pile supported a heavy crop of tomatoes, apparently grown from seeds in the Port Hope sewage. "Control" tomatoes for these tissues were two varieties of tomatoes purchased at a nearby supermarket. Plant samples from wooded areas were collected in the form of forest litter.

In the laboratory, moisture contents were determined for all sludge, soil and plant samples. Plant tissues were initially washed in tap water to remove soil particles. Husks were removed from grain samples (wheat, oats and barley), and corn kernels were removed from cobs. All plant, sludge and soil samples were oven-dried at 90° to 100°C, and milled with a mortar and pestel. Sludges were sieved through a 200-um mesh sieve so that the texture of samples was close to the texture of blind standards also submitted for analysis. Soils were sieved through a 500-um mesh to permit passage of all major soil constituents, and provide a uniform mixture for analysis. Plants were milled as finely as possible without sieving.

All samples of sludge, soil and plant tissues were submitted individually for uranium analysis and moisture content determination. Selected samples and composite samples were submitted for analysis of uranium decay products (Th-230, Ra-226, Pb-210 and Po-210), loss-on-ignition, trace elements and inorganic nitrogen, as shown in Table 2.1. CANMET tailings standards UTS-1 and UTS-2 were submitted as blind standards for determination of uranium decay products, and CANMET vegetation standards CLV-1 and CLV-2 were submitted as blind standards for uranium determination.

Radiochemical determinations were carried out by Monenco Analytical Laboratories in Calgary (all radionuclides except U), and by Atomic Energy of Canada Limited in Ottawa (U only). Uranium was determined by delayed neutron activation (Chiu and Dean, 1984). Samples for Ra-226 and Th-230 analysis were dissolved by KF-pyrosulphate fusion, and radioactivities were measured by high resolution alpha spectrometry (Chiu and Dean, 1984). Samples for Pb-210 and Po-210 analyses were digested in HF-HNO_3-$HClO_4$. Pb-210 was determined indirectly by measurement of Bi-210 using a beta-counter (Chiu and Dean, 1984). Po-210 was determined following the method of Smithson (1979) with the use of Po-208 as a tracer (Chiu, Monenco Analytical Laboratories, pers. comm.).

All other analyses were carried out at Beak Analytical laboratories in Mississauga. Trace metal concentrations were determined in selected sludge samples to provide chemical characterization, and to determine whether application rates of Port Hope sludge on farm land might be limited by metal content, as stipulated in Ontario's sludge utilization guidelines. Trace metal analyses were measured by plasma emission scan (SpectroMetrics, Inc., undated) of aqua regia extracts of sludge and soil samples (MOE, 1983). Ammonia and nitrate-nitrogen concentrations were determined in selected Port Hope sludges following procedures outlined by the American Public Health Association (1985). Data on recent sludge nitrogen and metal levels reported by the MOE were also compiled to permit the calculation of sludge application rates for agricultural fertilization, as outlined in the sludge guidelines.

TABLE 2.1: NUMBERS OF SLUDGE, SOIL AND PLANT TISSUES SUBMITTED FOR ANALYSIS AND PARAMETERS DETERMINED

	U	Decay Products	Loss-on-Ignition	Moisture Content	Trace Elements	Ammonium + Nitrate
Sludges						
Anaerobic Digest	3	1*	1	3	1*	1
Anaerobic Raw	3		1	3		1
Aerobic Digest	3	1*	1	3	1*	1
Aerobic Raw	3		1	3		
1981/82 Pile	1	1	1	1	1	
1983/84 Pile	1		1	1		
1985 Pile	1		1	1		
1985/86 Pile	1		1	1		
October 1986 Pile	1	1	1	1	1*	
1987 Drying Bed	1		1	1		
Pringle Creek	3		1	3		
Corbett Creek	3	1	1	3	1*	
Cobourg	3	1	1	3	1*	
Port Darlington	2		1	2		
Soils						
Farm 6						
• treated	1			1		
• controls	1			1		
Farm 14						
• treated	2			2		
• controls	1			1		
Farm 15						
• treated	1			1		
• controls	2			2		
Farm 21						
• treated	4	1**		4	1*	
• controls	1			1		
Oak-Pine Forest	1			1		
Plant Tissues						
1985/86 Sludge Pile	3			3		
1985 Sludge Pile	2			2		
1983/84 Sludge Pile	2			2		
1981/82 Sludge Pile	1			1		
Farm 6						
• treated	3			3		
• controls	1			1		
Farm 14						
• treated	3			3		
• controls	2			2		
Farm 15						
• treated	2			2		
• controls	4			4		
Farm 21						
• treated	3			3		
• controls	1			1		
Oak-Pine Forest	1			1		
Blind Standards						
CLV-1	1					
CLV-2	1					
UTS-1		1				
UTS-2		1				

* Composite of 3.

** Composite of 2.

3.0 RESULTS

3.1 Sludge Characterization

All Port Hope sludges showed concentrations of uranium significantly above those found in sludges from nearby municipalities. Concentrations in fresh digested Port Hope sludges ranged between 5.2 and 6.8 mg/L, as shown in Table A2.1 (Appendix 2) and summarized in Table 3.1. In comparison, concentrations of uranium in sludges from other regional WPCPs were less than 0.007 mg/L to 0.25 mg/L. In dry, stockpiled Port Hope sludges, uranium concentrations on a dry weight basis bracketed the dry weight concentrations found in fresh sludges, although concentrations were more variable in the older sludges (Table A2.1). There was no consistent trend in uranium concentration over time between 1981/82 and 1987, based on analysis of the dry sludges. Also, there was no consistent concentration trend in the fresh sludges over the survey period, indicating that the mid-summer shutdown at ERL was not reflected in a substantial change in sludge uranium levels.

Levels of U-238 decay products in fresh Port Hope sludges were similar to, or slightly greater than, those measured in sludge from Corbett Creek (Tables 3.1 and A2.2, Appendix 2). Cobourg sludges had somewhat lower levels of U-238 decay products than did either Port Hope or Corbett Creek sludges. Dry sludges from 1981/82 showed higher levels of U-238 decay products, on a dry weight basis, than found in other dried sludges or in fresh sludges, perhaps reflecting the effects of the old UO_3 plant in the older sludge.

The gamma field at 1 m above all dry piles was measured at 10 to 15 uR/h, compared to a background of about 5 to 10 uR/h, suggesting a minor source of gamma radiation. The 1981/82 pile showed a gradient from 10 uR/h near the top of the pile, to 15 uR/h near the bottom, suggesting some weathering of radioactivity from the top of the pile. Other piles showed relatively uniform levels of gamma radiation from top to bottom.

The elemental composition of Port Hope sewage sludges, as measured by the MOE, is summarized in Table 3.2. Nearly all of the inorganic nitrogen in anaerobic sludge is present as ammonium. Nitrate was found to be the dominant form in aerobic sludge, based on a single analysis in this study. Total inorganic nitrogen concentrations are much

TABLE 3.1: MEAN RADIONUCLIDE LEVELS* IN FRESH SLUDGES, NORMALIZED TO A WET SLUDGE BASIS

	U (ug/L)	U-238 (Bq/L)	Th-230 (Bq/L)	Ra-226 (Bq/L)	Pb-210 (Bq/L)	Po-210 (Bq/L)
Port Hope:						
• anaerobic digest	6,143 (541)	76	0.90	0.59	L 3	2.8
• anaerobic raw	5,237 (981)	64				
Port Hope:						
• aerobic digest	5,747 (752)	71	1.6	1.3	L 3	2.8
• aerobic waste	1,263 (276)	15.5				
Pringle Creek anaerobic digest	123 (18)	1.5				
Corbett Creek anaerobic digest	L 117	L 1.4	0.46	0.69	L 5	1.0
Cobourg anaerobic digest	43 (8.5)	0.53	L 0.09	L 0.09	L 1.8	0.45
Port Darlington anaerobic digest	L 44	L 0.54				

* For U, means of three values from all STPs except Port Darlington (two samples), standard deviation in parentheses; for other radionuclides, based on single analysis of three-sample composites (from Table A2.2).

TABLE 3.2: SLUDGE MONITORING DATA[1], AS PROVIDED BY THE TOWN OF PORT HOPE

(concentrations in mg/L, unless otherwise indicated)

	Port Hope Anaerobic		Port Hope Aerobic		Anaerobic-Aerobic Blended Sludge[3]		Mean N to Metal Ratio in Anaerobic Sludge		Mean N to Metal Ratio in Blended Sludge		Minimum Acceptable N to Metal Ratio for Landspreading[4]
	1986	Jan-Sep 87	1986	Jan-Sep 87	1986	Jan-Sep 87	1936	Jan-Sep 87	1936	Jan-Sep 87	
Cu	31	30	16	21	24	26	15	17	11	11	10
Ni	11	5.0	6.8	5.5	8.9	5.3	41	100	28•	56	40
Pb	6.7	6.2	3.4	4.3	5.1	5.7	68	80	49	52	15
Zn	29	26	17	19	23	23	16	19	11	13	4
Cd	0.48	0.26	0.28	0.22	0.38	0.24	950	1,900	660	1,200	500
Cr	4.4	3.6	2.1	2.9	3.3	3.3	103	140	76	90	6
Mo	0.33	L 0.34	L 0.35	L 0.28	L 0.34	L 0.31	1,400	GT 1,500	GT 740	GT 1,020	180
Se	0.20	0.16	0.16	0.12	0.18	0.14	2,300	3,100	1,400	2,100	500
Hg	0.11	0.12	0.05	0.08	0.08	0.10	4,100	4,200	3,200	3,000	1,500
Co	L 0.1	L 0.12	L 0.12	L 0.11	L 0.1	L 0.12	GT 4,500	GT 4,200	GT 2,500	GT 2,500	50
As	0.38	0.30	0.21	0.19	0.38	0.30	1,200	1,700	660	990	100
U	6.3	8.8	6.5	6.2	6.4	7.5	72	57	39	40	-
NH_4+NO_3-N	454	498	50	96	252	297					
NO_3-N[2]	L 1	L 1	66	66							
Solids (%)	3.83	3.64	1.73	1.98	2.79	2.81					

[1] Mean values.
[2] Based on analyses in this study.
[3] Based on a 50:50 blend of the two sludges.
[4] From MAF/MOE/MOH (1986).
• N to metal ratio below criterion.

greater in anaerobic sludge than in aerobic sludge, and a 50:50 mixture of aerobic and anaerobic sludge, as previously prepared for land application disposal of aerobic sludge, would be expected to have inorganic nitrogen levels that are averages of levels found in the two sludges. As noted in Section 1.0, only about 13% of the sludge produced at Port Hope is aerobic sludge; thus, about 26% of Port Hope sludge would be applied as blended sludge.

The metal criteria for sewage sludge used in land application are also given in Table 3.2, and are expressed as minimum ammonium plus nitrate-nitrogen to metal ratios. No criterion has been given for uranium, as this element is not thought to occur in high concentrations in most sewage sludges. The blended sludge from Port Hope has lower average nitrogen to metal ratios for most metals than does anaerobic sludge, due to the much lower nitrogen levels in the former. The average ratio for nickel in the blended sludge was lower than the sludge criterion in 1986, but greater than the criterion in the first half of 1987 (Table 3.2), indicating that sludge application rates for the blended sludge would at times be limited to a rate less than the recommended 135 kg of nitrogen per hectare per five years, if landspreading was permitted. There would be no limitation on landspreading of unblended anaerobic sludge based on average nitrogen to metal ratios.

Based on analysis of metals in single composite samples of digested sludges from Port Hope and two other WPCPs, metal contents of Port Hope sludges are, in many cases, similar to or less than those in the other sludges examined (Table A2.3, Appendix 2). Exceptions to this are aluminum and iron - two metals not included in the sludge criteria. Sludges in WPCPs using aluminum sulphate for phosphorus removal (e.g., Port Hope and Corbett Creek) are rich in aluminum, while WPCPs relying on high iron levels in sewage for phosphorus removal (e.g., Cobourg) have sludges poor in aluminum and rich in iron. In general, it may be concluded that the elemental composition of Port Hope sludges is typical of regional sludges in general, with the exception of higher uranium concentrations.

3.2 Effects of Sludge Application on Radionuclide Levels in Soil

Uranium concentations in soils previously fertilized with Port Hope sewage sludge ranged between 1.9 and 12.9 ppm, although all samples but one had uranium concentrations of

3.1 or less (Table 3.3). In comparison, uranium concentrations in control soils were 1.0 to 2.3 ppm. Concentrations in soils from the two woodlots sampled were the lowest of all samples (1.0 to 1.2 ppm), possibly reflecting the fact that neither Port Hope sludges nor phosphate fertilizers, which are also relatively rich in uranium (UNSCEAR, 1982), have been applied to these soils. At Farm 21, the degree of sludge application in each of four sections of the treated field is unknown, although accounts and records suggest that most of the sludge was applied to the mid-south section. In three of four cases, uranium concentrations in sludge-treated fields were higher than concentrations in nearby control soils, although, at one farm (14), half of the treated field had concentrations lower than the control while the other half had higher concentrations. With the exception of the mid-south section of the Farm 21 field, the difference in concentration between control and treated fields was in the order of 2 ppm or less, indicating that sludge application has resulted in a doubling of uranium concentrations in surface soil relative to background. It is noteworthy that the Farm 21 field sampled during this survey was the location identified in 1986 as having up to 22 ppm (Table A1.3, Appendix 1).

Uranium concentrations provided by the MOE for split samples based on gamma spectrometry tend to be about 0.5 ppm higher than concentrations measured by delayed neutron activation in this study (Table 3.3). Because the uranium concentration in a blind plant standard having 3.6 ppm uranium was accurately reported by the neutron activation analysis (Section 3.3), it is felt that this method provides a more reliable indication of uranium concentration within the concentration ranges found in this study.

Using records of sludge application rates, average concentrations of uranium in Port Hope sludge, the area of fields treated and an assumed soil density and plough depth, historic uranium loading rates and concentrations in surface soil can be calculated, as shown in Table 3.4. These calculations assume no loss of uranium due to weathering. In general, there is reasonable agreement between the predicted and observed uranium concentrations in sludge-treated soils, given the considerable uncertainties associated with the estimates of sludge volumes and areas of application. This table also shows the large discrepancies between prescribed and actual sludge application rates. It is noteworthy that, in two cases, predicted uranium concentrations were more than 2 ppm greater than measured concentrations, perhaps suggesting some weathering loss of uranium subsequent to sludge application. At Farms 15 and 21, there are no apparent differences between predicted and observed concentrations beyond the range of normal

TABLE 3.3: URANIUM CONCENTRATIONS (ppm dry weight) IN SOILS FERTILIZED WITH PORT HOPE SEWAGE SLUDGE

Sample		Concentration
Oak-Pine Forest Soil (Bewdley)[1]		1.0
Farm 6:	treated field	3.1
	control field (corn crop)[2]	1.7
Farm 14:	treated field (with crop)	1.9 (3.4)
	treated field (just planted)	2.8
	old field control[2]	2.3
Farm 15:	treated field	3.1 (3.7)
	control field (fallow, some wheat)[2]	1.4 (1.9)
	control woodlot[1]	1.2
Farm 21[3]:	far south section	1.7
	mid-south section*	12.9 (13.6)
	mid-north section	2.8/2.7**
	far north section	1.4
	control field (corn crop)[2]	1.5

1 Soils from mature wooded areas, no previous fertilizer use suspected.

2 Fields with suspected history of inorganic fertilizer application.

3 Sludge distribution over four field sections unknown.

* This field has history of high sludge application rates (see Table 3.4).

** Replicated sample.

Values in parentheses are split sample results provided by the MOE.

TABLE 3.4: COMPARISON OF MEASURED AND PREDICTED U CONCENTRATIONS IN SOILS FERTILIZED WITH PORT HOPE SLUDGE

Field	Volume Applied (m^3)	Prescribed Application (m^3)	Area (acres)	Year of Application	Estimated U Loading ($g \cdot ha)^{1}$	Predicted U Concentration $(ppm)^{2}$	Observed U Concentration (ppm)
Farm 6	6,718	573	10	1978-1981	9,960	5.9	3..
Farm 14	4,763	573	10	1977-1979	7,060	5.2	1.9'2.8•
Farm 15	1,454	401	7	1977	3,080	2.7	3.1
Farm 21	9,177	344	5••	1982-1984	27,200	12.8	12.9

1 Based on assumed U concentation of 6 ppm in wet sludge.

2 Calculated as background concentration (control field) plus U loading rate ($g \cdot m^{-2}$) divided by soil density (240 $kg \cdot m^{-2}$ based on a 15 cm plough depth).

• Two composite samples taken.

•• Considerable uncertainty regarding area treated.

background variation, indicating that weathering rates may be lower in these fields. The field sampled on Farm 21 was a cattle pasture that showed no sign of recent ploughing (perennial weed growth, heavily trampled) where inadequate aeration may prevent the maintenance of oxidizing conditions that would be expected to favour uranium mobility and loss from the surface soil (Dyck, 1978).

Incremental concentrations predicted for soils surveyed by the MOE are typically less than measured concentrations (Table A1.3, Appendix 1), and appear reasonable based on background concentrations in the order of 1.5 to 2 ppm uranium for farm fields (Table 3.3). In most cases, however, a mass balance cannot be clearly demonstrated due to a lack of information on specific aerial application rates or on background concentrations.

In the absence of any guidelines for uranium in the provincial sludge utilization guidelines, amounts of uranium and other radionuclides that would be incidentally added to soil through the landspreading of Port Hope sludge are assessed based on the maximum rate of nitrogen application permitted in the guidelines. Estimated uranium concentrations resulting in soils from the use of digested sludges from Port Hope and other WPCPs, based on adherence to the provincial sludge application guideline of 135 kg ammonium plus nitrate nitrogen per hectare every five years, are greater for Port Hope sludge than for sludges from other regional WPCPs (Table 3.5). Application of Port Hope sludge at this rate would add an estimated uranium concentration of 0.73 ppm in soil treated with anaerobic sludge, and 1.2 ppm in soil treated with blended anaerobic and aerobic sludge (Table 3.5). The volume-weighted average concentration added to surface soil for all Port Hope sludge would be 0.85 ppm, or about half of the background concentration of 1.4 to 2.3 ppm for regional farm fields that have not been treated with sludge. The reduction of about 33% in uranium loadings to the sewer system achieved by ERL by early August 1987 should result in proportional reductions in uranium concentrations in sludges and in loading rates to any soils fertilized with these sludges.

Estimated concentrations of U-238 decay products from Port Hope sewage sludges, based on nitrogen application rates of 135 kg per hectare per five years, are also higher than rates of application from the other WPCPs examined (Table 3.6).

It is of interest to compare uranium loading rates to soils, based on fertilization with Port Hope sewage sludge, other regional sludges, and typical phosphate fertilizers which

TABLE 3.5: URANIUM APPLICATION RATES AND INCREMENTAL CONCENTRATIONS, BASED ON MEAN URANIUM AND INORGANIC NITROGEN CONTENTS OF DIGESTED SLUDGES (ppm wet weight)

	U	NH_4-N	NO_3-N	Rate: Wet Sludge (m^3/ha·5 yrs)	Rate: U (g/ha·5 yrs)	Incremental Concentration ppm / 5 yrs
Port Hope Anaerobic	6.14	476[3]	-	284	1,740	0.73
Port Hope Blended[1]	5.95	275[3]	33	491	2,920	1.2
Port Hope - Volume Weighted Mean				340	2,030	0.8[4]
Pringle Creek	0.123	600* (1986)	-	225	27.7	0.012
Corbett Creek	L 0.117	950* (1986)	-	142	L 17	L 0.007
Port Darlington	L 0.044	351* (1986)	-	384	L 17	L 0.007
Cobourg-West	0.043	792* (Jan-Jul 1987)	2.5*	170	7.3	0.003

[1] Based on a 50:50 blend of aerobic and anaerobic sludge; NH_4 N content of combined sludge = 50% of average content in anaerobic sludge, NO_3-N content = 50% of concentration measured in one aerobic sludge sample (Table A2.1).

[2] U loading rate ($g \cdot m^{-2}$) ÷ soil density (240 $kg \cdot m^{-2}$, based on a 15 cm plough depth).

[3] Averages of values given in Table 3.2.

* Average concentrations for the periods indicated, as provided by Town and Regional offices.

TABLE 3.6: SOIL APPLICATION RATES OF U-238 DECAY PRODUCTS, BASED ON RADIONUCLIDE LEVELS AND INORGANIC NITROGEN CONTENTS OF DIGESTED SLUDGES

	Sludge Application Rate[1] (m^3/ha·5 yrs)	Radionuclide Application Rates (MBq/ha·5 yrs)			
		Th-230	Ra-226	Pb-210	Po-210
Port Hope Anaerobic	284	0.26	0.17	L 0.9	0.8
Port Hope Blended	491	0.62	0.47	L 1.5	1.4
Port Hope - Volume Weighted Mean	340	0.35	0.25	L 1.1	0.96
Corbett Creek	142	0.07	0.10	L 0.7	0.14
Cobourg	170	L 0.015	L 0.015	L 0.31	0.077

[1] From Table 3.5.

are relatively rich in uranium. Activity concentrations of U-238 decay chain radionuclides in phosphate fertilizers have been reviewed by UNSCEAR (1982), as shown in Table 3.7. From these data, typical concentrations in phosphate fertilizers are about 600 Bq/kg for U-238 and U-234, although concentrations vary considerably, and U-238 levels of 2,000 Bq/kg and greater were found in some fertilizers. If annual fertilizer application rates of 30 kg P_2O_5 to 150 kg P_2O_5 per hectare in the U.S. (National Plant Food Institute, 1963) are assumed to be reasonable for the Port Hope area, radionuclide application rates may be readily calculated, as shown in Table 3.8. From this table, it is apparent that average uranium concentrations would be greater in soils fertilized with Port Hope sludge than in soils fertilized with "average" phosphate fertilizer. Application rates of uranium from other sewage sludges would not differ substantially from application rates using phosphate fertilizers. The higher uranium application rates that would arise from use of Port Hope sludge are attributed to the much greater mass of sludge fertilizer applied (about 300,000 kg per five years) compared to a 100 kg per year application rate for phosphate fertilizer. The uranium concentration in phosphate fertilizer (about 600 $Bq \cdot kg^{-1}$) is actually much higher than the 6 ppm (74 $Bq \cdot kg^{-1}$) found in the Port Hope sludge.

Typical quantities of U-238 decay products added incidentally from the use of phosphate fertilizers are similar to the quantities added through the use of Port Hope sludges or other sludges, based on typical activity concentrations of 600 Bq/kg for Th-230 and 400 Bq/kg for Ra-226 and decay products (UNSCEAR, 1982). Thus, replacement of phosphate fertilizer with sewage sludge from Port Hope or other regional WPCPs will not substantially alter levels of these radionuclides in soils. On this basis, the radiological implications of sludge use are the same as those for inorganic fertilizer use, and a more detailed evaluation of the application of these radionuclides to soil through sludge may be unwarranted. However, if one application of sludge every five years replaces only one year of inorganic fertilizer use, then consideration of the contribution of U-238 decay products from Port Hope sludge may be justified in a radiological analysis. In the event this may be the case on some farms, this analysis was carried out. Table 3.9 presents incremental concentrations of U-238 decay products in soil due to fertilization with Port Hope and other sewage sludges. For all of these radionuclides, the concentrations added in five years of application of Port Hope sludge are less than 2% of the natural background concentration of 0.025 $Bq \cdot g^{-1}$ for soils (UNSCEAR, 1982). Pb-210 and Po-210 occur at activities in excess of Ra-226 but, due to their short half-lives (22 years for Pb-

TABLE 3.7: ACTIVITY CONCENTRATIONS OF NATURALLY OCCURRING RADIONUCLIDES IN PHOSPHATE FERTILIZERS ($Bq \cdot kg^{-1}$) (from UNSCEAR, 1982)

Type of Fertilizer	Country	U-238	Th-230	Ra-226	Pb-210	Po-210
Treated Rock Phosphates						
Apatite	USSR			30	25	30
Phosphorite	USSR			390	380	480
Concentrate obtained by flotation	USSR			420	390	290
Calcined, ground soft, partly converted rock phosphate, etc.[1]	FRG	670		480		
One-Component Phosphate Fertilizers						
Superphosphate	FRG	529		520		
Superphosphate	USSR			110	300	150
Superphosphate	USA	740	670	790		
Superphosphate	Belgium	1,100		910		
Triple superphosphate	FRG	800		230		
Triple superphosphate	USA	2,100	1,800	780		
PK-Fertilizers[2]	FRG	410		370		
NP-Fertilizers						
NP-fertilizers[1]	FRG	920		310		
Ammonium phosphate	USSR			100		
Nitrophosphate	USSR			850	870	920
Nitroammonium phosphate	USSR				15	15
Monoammonium phosphate	USA	2,000	1,800	20		
Diammonium phosphate	USA	2,300	2,400	210		
NPK-Fertilizers[3]						
NPK	FRG	440		270		
NPK	USSR			9	15	20
NPK	Belgium	470		210		
Basic Slag	Belgium	23		19		

[1] Assuming a P_2O_5-to-fertilizer mass concentration ratio of 0.28.
[2] Assuming a P_2O_5-to-fertilizer mass concentration ratio of 0.16.
[3] Assuming a P_2O_5-to-fertilizer mass concentration ratio of 0.13.

TABLE 3.8: ANNUAL APPLICATION RATES OF U-238 DECAY CHAIN RADIONUCLIDES IN SOILS FERTILIZED WITH SEWAGE SLUDGES AT PRESCRIBED RATES[1] AND WITH INORGANIC PHOSPHATE FERTILIZERS[2]

	U	Th-230	Ra-226	Pb-210	Po-210
Port Hope Sludge (volume-weighted mean of anaerobic and aerobic sludges)	410	0.070	0.05	L 0.22	0.19
Corbett Creek Sludge	L 3.4	0.014	0.020	L 0.14	0.028
Cobourg Sludge	1.5	L 0.003	L 0.003	L 0.062	0.015
Pringle Creek Sludge	5.5	-	-	-	-
Port Darlington Sludge	L 3.4	-	-	-	-
"Average" Phosphate Fertilizer	4.9	0.060	0.040	0.040	0.040

[1] Based on 135 kg inorganic nitrogen·ha^{-1}·5 yr^{-1}, or 20% of values given in Tables 3.5 and 3.6. Units are g·ha^{-1}·yr^{-1} for U and MBq·ha^{-1}·yr^{-1} for decay products.

[2] Inorganic phosphate fertilizer assumed to contain 600 Bq·kg^{-1} (48.8 mg·kg^{-1}) of uranium, 600 Bq·kg^{-1} of Th-230, and 400 Bq·kg of Ra-226, Pb-210 and Po-210, applied at an annual rate of 100 kg·ha^{-1}.

TABLE 3.9: INCREMENTAL CONCENTRATIONS ($Bq \cdot g^{-1}$) OF U-238 DECAY PRODUCTS EXPECTED IN SOILS FERTILIZED WITH PORT HOPE SEWAGE SLUDGE AND OTHER SEWAGE SLUDGES[1]

	Th-230	Ra-226	Pb-210[2]	Po-210[2]
Port Hope Sludge (volume-weighted mean of anaerobic and aerobic sludges)	1.5E-4	1E-4	4E-4	4E-4
Corbett Creek Sludge	3E-5	4E-5	6E-5	6E-5
Cobourg Sludge	L 6E-6	L 6E-6	3E-5	3E-5

[1] Incremental concentrations added to soils from sludge application over a five-year period, based on radionuclide application rates given in Table 3.6 divided by (10,000 $m^2 \cdot ha^{-1}$ x 240 $kg \cdot m^{-2}$ bulk density for a 15-cm plough depth).

[2] Pb-210 and Po-210 are assumed to be in secular equilibrium.

210), these will gradually decay into equilibrium with their closest long-lived parent, Ra-226.

3.3 Uptake of Uranium by Plants

Concentrations of uranium in plant tissues sampled during this study, along with corresponding concentrations in soil or dry sludge, are presented in Table 3.10. In most cases, edible plant tissues (grain, corn, soy beans and tomatoes) had uranium concentrations below the detection limit of 0.2 ppm dry weight, including tomatoes growing on undiluted Port Hope sludge. The only instance where detectable uranium concentrations occurred in edible plant tissue was in corn from a control field where sludge has apparently never been applied. Shoots (leaves and stems) generally also had uranium concentrations near or at the detection limit in all species grown on soil, although shoots of plants growing on sludge piles had up to 1.5 ppm dry weight of uranium. The highest uranium concentrations in plant tissues (dry weight basis) occurred in roots, which contained 0.3 to 0.5 ppm in control samples, 0.7 to 1.4 ppm in samples from sludge-treated fields, and 4 ppm in tomatoes growing in sludge at the WPCP.

In comparison, McLaughlin (1986a) reported uranium concentrations in edible herbs of 0.08 to 0.34 ppm dry weight in sludge-amended soils containing up to 23 ppm of uranium. In a survey of vegetable gardens in Port Hope, Tracy et al. (1983) reported uranium concentrations (fresh weight) of less than 0.01 ppm in control samples (soil concentration of 2 ppm dry weight) and maximum concentrations of 0.2 ppm in vegetables (carrots) grown in contaminated soils (having up to 420 ppm dry weight). The sources of contamination in this latter study were not identified, although reported gamma radiation levels of 20 to 2,000 $uR \cdot h^{-1}$ over these gardens are much greater than levels found over sewage sludge piles in this study, indicating that the radiation source was probably historic waste. Atmospheric deposition of airborne uranium is also an important local source of uranium in plant tissues in Port Hope, as demonstrated by concentrations in excess of 100 ppm in maple foliage from trees growing near the ERL refinery (McLaughlin, 1986b).

Plant tissues may accumulate uranium by atmospheric deposition of soil and dust particles, as well as by root uptake. The soil-to-plant concentration factor, or B_v value, is often used to describe bioaccumulation of organic and inorganic substances from soil,

TABLE 3.10: U ANALYSIS: SOIL/DRIED PORT HOPE SLUDGE-PLANT TISSUES
Concentrations in ppm dry weight; ppm fresh weight in parentheses for plant tissues

Sample		Soil/ Sludge	Plant Type	Plant Tissues			
				Shoots	Roots	Grain/Fruit	Other
Oak-pine Forest Soil (Newdley)		1.0	oak-pine litter	-	-	-	L 0.2 (L 0.17)
Farm 6:	treated field	3.1	soy beans	L 0.2 (L 0.044) (leaves)	-	L 0.2 (L 0.032) (whole pods)	-
			corn	-	-	L 0.2 (L 0.017)	-
	control field	1.7	no plant sample	-	-	-	-
Farm 14:	treated field (with crop)	1.9	oats/barley	L 0.2 (L 0.067)	0.7 (0.35)	L 0.2 (L 0.12)	-
	treated field (just planted)	2.8	(no plant sample)	-	-	-	-
	old field control	2.3	goldenrod	L 0.2 (L 0.066)	0.3 (0.12)		
Farm 15:	treated field	3.1	hay	L 0.2 (L 0.11)	1.4 (0.79)	-	-
	control field	1.4	wheat	L 0.2 (L 0.16)	0.3 (0.19)	L 0.2 (L 0.17)	-
	control woodlot	1.2	maple-beech litter	-	-	-	0.4 (0.27)
Farm 21:	far south section	1.7	pasture grass	0.1 (0.035)	-	-	-
	mid-south section	12.9	pasture grass	L 0.2/L 0.2 (L 0.067)	-	-	1.7 (cattle manure)
	mid-north section	2.8/2.7	pasture grass	0.3 (0.096)	-	-	-
	far north section	1.4	no plant sample	-	-	-	-
	control field	1.5	corn	-	-	0.5 (0.072)	-
1985/86 Sludge Pile		58/61	tomatoes	0.2 (0.027) (leaves and stems)	4.0 (0.55)	L 0.2 (L 0.019)	-
			control tomatoes (supermarket)	-	-	L 0.2 (L 0.01)	-
1985 Sludge Pile		520	catnip	0.9 (0.23)	-	-	-
			grass	1.0 (0.26)	-	-	-
1983/84 Sludge Pile		250	catnip	1.5 (0.61)	-	-	-
			grass	0.4 (0.10)	-	-	-
1981/82 Sludge Pile		470	grass	1.2 (0.46)	-	-	-
Blind Plant Standard (CLV-1)		-	spruce twigs	-	-	-	89
True Value		-		-	-	-	87
Blind Plant Standard (CLV-2)		-	spruce needles	-	-	-	3.6
True Value		-		-	-	-	3.6

and applied in environmental pathways analyses to predict radiation doses from radioactive substances in soils. B_v's are highly variable and typically show a log-normal frequency distribution. Snodgrass et al. (1986) compiled B_v values for plant tissues from the literature, and reported a geometric mean value of 0.0019 for uranium in both above- and below-ground vegetables (expressed on a fresh weight basis for plants). Baes et al. (1984) gave a default B_v value for food-chain modelling of 0.0085 for uranium in non-reproductive plant parts, and 0.004 for uranium reproductive plant parts (expressed on a dry weight basis for plants). Letourneau (1987) reported a range of B_v values of 0.00001 to 0.002 for food crops, based on a literature review. B_v values calculated from data in this study have geometric means of 0.018 (dry weight basis) and 0.0063 (fresh weight basis) (Table 3.11), which are somewhat greater than literature-derived values given above, possibly reflecting a more bioavailable, organically-bound uranium source in sludge-amended soils. The most appropriate values for a pathway analysis and radiological assessment of the agricultural use of Port Hope sewage sludge is the higher value for uranium obtained in this study. It should be noted that the average B_v value derived in Table 3.11 is based on data on both edible and non-edible plant tissues sampled in this study. Because most edible tissues (including all grown on sludge-amended soils) had uranium concentrations that were below the analytical detection limit, it was felt that B_v values from other plant tissues and non-edible species should be included to provide a larger database, and to include tissue types that are edible in other plant species (e.g., roots in carrots, leaves in lettuce). Application of the relatively high B_v value derived here in a radiological assessment is more conservative than would be the application of lower factors reported in other studies.

Concentrations of U-238 decay products were not determined in plant tissues in this study. Appropriate default values for radionuclide uptake in food crops have been selected as: Th-230, 0.0005; Ra-226, 0.005; Pb-210, 0.001; Po-210, 0.0002 based upon ranges given in Letourneau (1987). These are the uptake values used for the radiological assessment.

TABLE 3.11: SOIL TO PLANT CONCENTRATION FACTORS, B_v, FOR URANIUM (ppm plant/ppm soil)

		Dry Weight Basis	Fresh Weight Basis
Oats and Barley:	Shoots	L 0.105	L 0.035
	Roots	0.37	0.18
	Grain	L 0.105	L 0.063
Goldenrod:	Shoots	L 0.087	L 0.029
	Roots	0.13	0.052
Grass:	Shoots	0.059	0.021
		L 0.016	L 0.005
		0.109	0.035
		0.0019	0.0005
		0.0016	0.0004
		0.0026	0.001
Corn:	Kernels	0.33	0.048
		L 0.064	L 0.0055
Soybeans:	Pods and Beans	L 0.065	L 0.010
	Leaves	L 0.065	L 0.014
Tomatoes:	Leaves and Stems	L 0.0033	L 0.00045
	Roots	0.0667	0.0092
	Fruit	L 0.0033	L 0.0003
Catnip:	Shoots	0.0017	0.00044
		0.0060	0.0024
Geometric Mean (excluding less than values)		0.018	0.0063

4.0 DISCUSSION OF RADIOLOGICAL CONSIDERATIONS

Farmers using Port Hope sewage sludges to fertilize their fields may be assumed to be the individuals most exposed to uranium from the sludge, since they work on the treated fields and may consume some of the produce grown on the sludge-amended soils. The radiological risk associated with the agricultural use of Port Hope sewage sludge arises through inhalation of contaminated dust during cultivation activities, consumption of crops grown on contaminated soils, and exposure to gamma radiation field given off by the dust and by soil. In this section, radiation doses are calculated for natural uranium (U-238 and its short-lived daughters, U-234 and U-235 and its short-lived daughter), as well as for U-238 decay products. It should be noted that the incremental doses calculated here are conservative in that no account is taken for the "routine" dose normally attributed to the application of the inorganic fertilizers that Port Hope sludge would replace in normal agricultural use. It should also be pointed out that these incremental doses are strictly those associated with sludge use, and do not include the contributions of background uranium concentrations in soil to the total doses received through each pathway.

The doses calculated for each pathway in Subsections 4.1 to 4.4 are for a scenario where the quantity of sludge applied is equivalent to 135 kg of inorganic nitrogen per hectare. This is the maximum quantity that may be applied every five years, as stipulated in the sludge utilization guidelines.

4.1 Internal Exposure from Inhalation

The respirable airborne concentration of dust containing uranium from the sludge is assumed to be 0.5 $mg \cdot m^{-3}$ while the farmer is actively tilling the land. This value is within the range of dust concentrations measured for similar conditions or used in previous comparable assessments (IAEA, 1987). Assuming an average inhalation rate of 3.3×10^{-4} $m^3 \cdot s^{-1}$ for workers (IAEA, 1987), an annual exposure period of 200 h while ploughing and cultivating, and a uranium concentration of 0.85 ppm due to sludge use (Table 3.5), the annual inhalation dose may be calculated as follows:

$$H_{inh} = C_a \times I \times t \times DCF_{inh} \qquad (4.1)$$

where: H_{inh} = committed effective dose equivalent for one year of uranium intake by inhalation, Sv,

C_a = concentration of uranium from sludge mixed with airborne dust particles generated from soils fertilized with Port Hope sludge, 0.5 mg soil$\cdot m^{-3}$ x 0.85 ppm U = 4.25×10^{-4} ug U$\cdot m^{-3}$,

I = inhalation rate, 3.3×10^{-4} $m^3 \cdot s^{-1}$,

t = duration of exposure each year, 200 h$\cdot yr^{-1}$, or 7.2×10^5 s$\cdot yr^{-1}$, and

DCH_{inh} = committed effective dose equivalent conversion factor for inhalation of natural uranium, 1.0×10^{-6} Sv$\cdot ug^{-1}$ (as derived in Lush et al., 1985, from dose conversion factors given in Johnson and Dunford, 1983).

Following Equation 4.1, the inhalation dose due to uranium added to soil from application of Port Hope sludge is 1.01×10^{-7} Sv$\cdot yr^{-1}$ (Table 4.1). The corresponding calculations for inhalation of U-238 decay products, based on the dose conversion factors given in Table A3.4, and on soil concentrations resulting from sludge application as given in Table 3.9, are presented in Table 4.1. The dose due to radon inhalation is not calculated, as radon gas will be quickly dispersed from the site before significant ingrowth of radon daughters can occur.

4.2 Internal Exposure from Ingestion

The annual dose attributed to the consumption of crops grown on sludge-amended soils depends on the quantities of produce consumed and on the concentration of uranium in the produce. Assuming that the farmer consumes an average of 40 kg of produce from sludge-amended fields on his farm, the annual dose due to the ingestion of uranium accumulated by crops from sludge applied to farm soil may be calculated as follows:

$$H_{ing} = C_g \times B_v \times I_p \times DCF_{ing} \qquad (4.2)$$

where: H_{ing} = committed effective dose equivalent from one year of intake of uranium in produce, Sv,

C_g = concentration of uranium added to the ground from sludge application, 0.85 ppm,

B_v = soil-to-plant concentration factor, 0.0063,

TABLE 4.1: SUMMARY OF DOSES ($Sv \cdot yr^{-1}$) BY PATHWAY DUE TO EXPOSURE TO NATURAL URANIUM AND U-238 DECAY PRODUCTS IN SOIL FROM APPLICATION* OF "AVERAGE" PORT HOPE SEWAGE SLUDGE AS FERTILIZER

	U-nat	Th-230	Ra-226	Pb-210	Po-210	Totals
Inhalation	1.01E-7	1.44E-9	3.09E-11	1.66E-10	1.19E-10	1.0E-7
Ingestion	4.28E-7	1.05E-8	6.40E-9	2.56E-8	1.70E-9	4.7E-7
Cloud Immersion	4.50E-15	9.05E-19	1.06E-17	8.3E-18	5.43E-20	4.5E-15
Groundshine	7.86E-9	7.11E-13	6.93E-9	5.55E-12	1.41E-13	1.5E-8
TOTALS	5.4E-7	1.2E-8	1.3E-8	2.6E-8	1.8E-9	5.9E-7

* Based on an application of 135 kg of inorganic nitrogen in sludge per hectare.

I_p = the rate of intake of contaminated produce, 40 $kg \cdot yr^{-1}$, and

DCF_{ing} = committed effective dose equivalent conversion factor for ingestion of natural uranium, 2.0×10^{-9} $Sv \cdot ug^{-1}$ (as derived in Lush et al., 1985, from dose conversion factors given in Johnson and Dunford, 1983).

Following Equation 4.2, the dose from uranium ingestion is 4.28×10^{-7} $Sv \cdot yr^{-1}$ for soils fertilized with Port Hope sludge (Table 4.1). The corresponding calculations for ingestion of U-238 decay products, based on the dose conversion factors and soil-to-plant factors given in Table A3.4, and on soil concentrations given in Table 3.10, are presented in Table 4.1.

4.3 External Exposure from Suspended Dust

Airborne dust contaminated with uranium from the sludge will expose the farmer immersed in the dust to gamma radiation. The dose received by the farmer will depend on the exposure period and the airborne uranium concentration. Assuming that the farmer is exposed to dust from sludge-fertilized fields for 200 h per year with an airborne uranium concentration of 4.25×10^{-4} $ug \cdot m^{-3}$ (see Subsection 4.1) due to sludge application, the dose may be readily calculated using the semi-infinite cloud model:

$$H_{ext(d)} = C_a \times DCF_a \times f_t \qquad (4.3)$$

where: $H_{ext(d)}$ = committed effective dose equivalent from one year of exposure to gamma radiation from suspended dust, Sv,

DCF_a = dose conversion factor for immersion in a semi-infinite cloud of natural uranium, 4.64×10^{-10} $Sv \cdot yr^{-1} \cdot ug^{-1} \cdot m^3$ (as derived in Lush et al., 1985, from dose conversion factors given in Kocher, 1983), and

f_t = fraction of time that the farmer is exposed to the plume, 200 $h \cdot yr^{-1}$/8,760 $h \cdot yr^{-1}$ = 0.0228.

Using Equation 4.3, the external radiation dose received by the farmer due to immersion in the cloud of uranium from sludge in airborne dust is 4.50×10^{-15} $Sv \cdot yr^{-1}$ (Table 4.1). The corresponding calculations for immersion in a cloud of U-238 decay products, calculated from dose conversion factors given in Table A3.4, and on incremental soil concentrations given in Table 3.10, are presented in Table 4.1.

4.4 External Exposure from Contaminated Ground

Once worked into the soil, natural uranium from the sludge results in an external radiation source to the farmer working on his sludge-amended fields. The source may be approximated as a 15-cm deep contaminated layer, completely mixed due to the effects of ploughing. Exposure to a gamma source from a layer of material can be approximated by slab source models. Kocher and Sjoreen (1985) calculated gamma dose rate conversion factors for various soil thicknesses and gamma photon energies, using the standard point kernal integration method and the Berger form for energy buildup factors for soil.

The dose rate conversion factor ($Sv \cdot yr^{-1}$ per $Bq \cdot cm^{-3}$) for a 15-cm thick layer of soil contaminated with natural uranium (U-238, and its short-lived daughers, U-234, and U-235 and its short-lived daughters) is derived in Appendix 3 using Kocher and Sjoreen's calculations, based on soil concentration units for U-238 (the dominant isotope). Dose rate conversion factors ($Sv \cdot yr^{-1}$ per $Bq \cdot cm^{-3}$) for exposure above 15-cm thick layers of U-238 decay products are similarly derived in Appendix 3.

The effective dose received by the farmer exposed for 200 $h \cdot yr^{-1}$ to natural uranium from sludge-amended soil is calculated as follows:

$$H_{ext(g)} = C_g \times \rho_s \times 1.23 \times 10^{-2}\ Bq \cdot ug^{-1} \times DCF_g \times f_t \qquad (4.4)$$

where: $H_{ext(g)}$ = committed effective dose equivalent from one year of exposure to gamma radiation from contaminated ground,

C_g = concentration of uranium in soil from sludge application, 0.85 ppm,

ρ_s = soil bulk density, assumed to be 1.6 $g \cdot cm^3$,

1.23×10^{-2} = conversion from ug to Bq for U-238,

DCF_g = dose conversion factor for exposure to natural uranium from a 15-cm thick slab source, 2.06×10^{-5} $Sv \cdot yr^{-1}$ per $Bq \cdot cm^{-3}$ (as derived in Appendix 3), and

f_t = fraction of time that the farmer is exposed to the soil, 200 $h \cdot yr^{-1}$/8,760 $h \cdot yr^{-1}$ = 0.0228.

Following Equation 4.4, the dose due to exposure to "groundshine" is from natural uranium 7.86×10^{-9} $Sv \cdot yr^{-1}$ for soils fertilized with Port Hope sludge (Table 4.1).

Corresponding doses due to groundshine from U-238 decay products, calculated from dose conversion factors derived in Appendix 3, and on incremental soil concentrations given in Table 3.10, are presented in Table 4.1.

4.5 Summary of Radiological Considerations

The dose received by a hypothetical farmer fertilizing his fields with Port Hope sewage sludge at the prescribed rate is estimated as 0.00059 $mSv \cdot yr^{-1}$, which is the sum of the doses from each of the four exposure pathways and five radionuclides (Table 4.1). About 91% of this dose is attributed to uranium content from the sludge. The ingestion pathway contributes most to the total dose for all radionuclides.

If a farmer fertilizes his fields several times over many years, so that the incremental uranium concentration in soil is 8 ppm and the total concentration is at the safe upper limit for chemical toxicity to plants, 10 ppm (i.e., background of 2 ppm plus 8 ppm; see Section 5.0), then the incremental dose to the farmer would be (8 ppm U/0.85 ppm U) times 0.00059 $mSv \cdot yr^{-1}$, or 0.0056 $mSv \cdot yr^{-1}$. This calculation assumes either that no radionuclides are lost between applications due to decay and weathering, or that the fractional loss rates of all radionuclides are equal. In fact, some radioactive decay of Pb-210 and Po-210 will occur between sludge applications because Pb-210 is added in excess of its long-lived parent, Ra-226. This loss will tend to slightly reduce the dose rate over time. About 50 years of sludge application at the maximum rate prescribed in the provincial guidelines would be required before soil uranium levels reach 10 ppm, assuming no loss due to weathering.

In comparison with other sources of radiation, Port Hope sewage sludge contributes very little radiation dose to the farmer, as shown in Table 4.2. Natural background sources of radiation contribute an annual effective dose equivalent of about 3,400 times more than is contributed by one application of sewage sludge, and about 360 times more than would be contributed by the addition of 8 ppm uranium to soil. An annual dose equivalent of 0.00059 mSv from sludge application is less than half of the average dose equivalent received during a one-hour flight on a commercial aircraft, and is only about 3% of the effective dose equivalent typically received during a dental x-ray examination (comparative statistics from UNSCEAR, 1982). The International Atomic Energy Agency (1987) has designated practices that result in an annual effective dose equivalent of 0.01

TABLE 4.2: RADIATION DOSES RECEIVED FROM EXPOSURE TO SLUDGE AND FROM OTHER ROUTINE SOURCES

Source	Dose
Fields Treated with Port Hope Sludge (0.85 ppm U added to soil)[1]	0.00059 $mSv \cdot yr^{-1}$
One-hour Flight @ 8 km Altitude[2]	0.00135 mSv
Fields Treated Repetitively Until 8 ppm U Added to Soil (at least 50 years of treatment)[3]	0.0056 $mSv \cdot yr^{-1}$
Trivial Dose Limit[4]	0.01 $mSv \cdot yr$
Dental x-ray Exam[2]	0.023 mSv
Natural Background[2]	2 $mSv \cdot yr^{-1}$

[1] From Table 4.1.
[2] From UNSCEAR (1982).
[3] (8/0.85 ppm U) times 0.00059 $mSv \cdot yr^{-1}$.
[4] From IAEA (1987).

mSv or less as trivial from a radiological standpoint and exempt from regulatory control. This IAEA limit is 16 times the annual dose received per application by the hypothetical farmer, and nearly twice the annual dose that would be received after repetitive sludge application to the point where 8 ppm of uranium has been added.

5.0 DISCUSSION OF OTHER CONSIDERATIONS

In evaluating the radiological consequences of landspreading of Port Hope sludge, it became clear to the study team that issues relating to plant toxicity as a result of uranium build-up in soil and the possibility of human toxicity as a consequence of consuming plants on these soils should also be addressed, because natural uranium is, under most circumstances, considered to be more chemically toxic than it is radiotoxic. These two areas, although outside of the primary scope of this study, are briefly addressed here for the sake of completeness.

5.1 Plant Toxicity

At sufficiently high uranium concentration in soil, uranium may be chemically toxic to plants. Zhukov and Zudilkin (1971) grew spring wheat on soils experimentally contaminated with soluble uranyl nitrate, and found that wheat yield was reduced by 50% at soil concentrations of 50 ppm uranium, while no effect occurred at 10 ppm. Because cereal crops appear to be among the most sensitive to metal toxicity (D. McLaughlin, MOE - Phytotoxicity Section, pers. comm.), 10 ppm of soluble uranium in soil may be near the upper limit of non-toxic concentrations for crops. It is emphasized, however, that environmental standards for soil contaminants should be based on more phytotoxicity information than is currently available for uranium. The apparently unimpaired growth of tomatoes in dried sewage sludge containing 60 ppm uranium, and the colonization of older sludge piles containing up to 500 ppm uranium by various grasses and weeds at the Port Hope WPCP, suggest that uranium in the sludge is less bioavailable and less toxic than are more soluble forms. On this basis, the designation of 10 ppm as the safe upper limit for uranium in soils treated with Port Hope sewage sludge is probably conservative. With a typical background uranium concentration of about 2 ppm found in regional farm fields in this study, 8 ppm of uranium could be added to soil through sludge application before reaching this 10 ppm limit.

5.2 Human Toxicity

Based upon animal and human studies, Health and Welfare Canada has determined that an annual daily ingestion of up to 70 ug of uranium by an adult should not have any chemically toxic effect. This total maximum consumption figure of 70 ug U daily, or

about 25,000 ug U annually, is the basis upon which national drinking water guidelines have been set (HWC, 1980). If a farmer were to fertilize his fields with Port Hope sludge containing the uranium values found in this study, and he were to consume the same quantity of crops from these fields as used in the radiological analysis (40 $kg \cdot yr^{-1}$), then his annual intake, after five years of sludge application at the maximum rate, is calculated at 210 $ug \cdot yr^{-1}$ or less than 1% of the maximum recommended by Health and Welfare Canada. If he were to fertilize his fields to the level where available data suggest plant growth may be affected (10 ppm U in soil), he would still ingest less than 10% of the maximum level recommended by Health and Welfare Canada.

5.3 Summary of Other Considerations

Based upon the available data, it would appear that phytotoxicological considerations may be more limiting to the landspreading of Port Hope sludges than are human chemical toxicity or radiotoxicity considerations.

6.0 IMPLICATIONS OF PORT HOPE SLUDGE UTILIZATION

6.1 Radiological Considerations

As outlined in Subsection 4.5, the annual effective dose equivalent to farmers using the sludge is expected to be trivial, based on national and international standards and normal exposure to natural background sources of radiation. More than 90% of this trivial dose is attributed to natural uranium released into the sewer by the licensee (ERL), and the remainder is attributed to U-238 decay products from unidentified sources in the sewershed. Doses that may be expected after repetitive applications of sludge to the point where uranium levels in soil may begin to elicit toxic effects in sensitive crops remain trivial. The individual dose received by farmers using the sludge is expected to decline as loadings of uranium to the sewershed are reduced by the licensee. The actual doses received will vary somewhat according to the actual quantity of crops consumed and on the type of plant tissues consumed. Although not calculated here, the dose rate due to sludge handling is much less than the dose rate that occurs during handling of normal inorganic fertilizers, because U-238 decay chain radionuclides are typically much more concentrated in inorganic fertilizers.

6.2 Other Considerations

The dietary intake of uranium due to an annual consumption of 40 kg of crops grown on sludge-treated soils is considerably less than the annual maximum intake currently specified by Health and Welfare Canada, even in instances where sludge has been applied to a soil concentration that may begin to elicit toxic effects in sensitive crops. Thus, the chemical toxicity implications to persons consuming crops grown on soils fertilized with Port Hope sewage sludge would appear to be secondary to phytotoxicological effects.

A soil uranium concentration of 10 ppm has been suggested as the highest concentration causing no reduction in crop yield, based on a single experiment measuring wheat yield in soils treated with uranyl nitrate (Zhukov and Zudilkin, 1971). It is expected that a threshold toxic concentration for uranium in soils treated with Port Hope sewage sludge would be somewhat higher than 10 ppm, because the 10 ppm criterion is derived using a soluble form of uranium, while uranium in soils treated with Port Hope sludge may be less bioavailable. This is supported by the apparently unaffected growth of tomatoes on

recently stockpiled sludge having about 60 ppm uranium, and the growth of various plants on older sludge piles at up to 500 ppm uranium. The Canadian Council of Resource and Environment Ministers (CCREM, 1987) has set a tentative water quality guideline for irrigation waters based on this 10 ppm criterion. The recommended maximum uranium concentration in irrigation water is given as 0.01 $mg \cdot L^{-1}$ for continuous or intermittent use on all soils, and 0.1 $mg \cdot L^{-1}$ for use up to 20 years on neutral and alkaline fine-textured soils, based on an assumed irrigation rate of 1 $m \cdot yr^{-1}$. Irrigation at 1 $m \cdot yr^{-1}$ using water at 0.01 and 0.1 mg $U \cdot L^{-1}$ would result in uranium application rates of 10 and 100 $mg \cdot m^{-2} \cdot yr^{-1}$, respectively. The annual application rate of 41 $mg \cdot m^{-2} \cdot yr^{-1}$ uranium, which could result from the use of Port Hope sewage sludge as fertilizer at the rate prescribed by the MAF/MOE/MOH (1986) guidelines, is less than half of the upper limit indicated by these tentative irrigation guidelines. This application rate may be expected to decline as uranium loadings to the sewer are reduced by ERL.

If no weathering loss of uranium from the surface soil was to occur between applications of sewage sludge, about 50 years of sludge application at the maximum rate permitted under the provincial guidelines would be required before an incremental concentration of 8 ppm and a total (including background) of 10 ppm in soil is reached. Corresponding periods required to reach maximum recommended concentrations of stable metals in soils treated with sludges having the minimum nitrogen to metal ratios given in the sludge application guidelines are also in the order of 50 years (range 25 to 55 years). Thus, if 10 ppm is an acceptable maximum concentration for uranium in soil, then Port Hope sludge application at the prescribed rate will result in uranium accumulation rates that are consistent with acceptable accumulation rates of other metals.

Uranium is relatively mobile, particularly under oxidizing conditions (e.g., Dyck, 1978). Thus, some leaching of uranium added to surface soils from sludge application is expected, particularly under oxidizing conditions. As noted in Section 3.2 of this report, there appears to be some inconclusive evidence for a weathering loss of uranium from some soils that have been fertilized with Port Hope sewage sludge. A weathering half-life of ten years for total uranium in surface soils would result in the return to a background concentration of 2 ppm five years after 0.85 ppm has been added through sludge application, i.e., there would be no net build-up in soil (assuming first order kinetics). A weathering half-life of 35 years for uranium in surface soil would result in a steady-state soil concentration of 10 ppm in soils fertilized at the rate prescribed by the

sludge guidelines. The Commission of European Communities (CEC, 1979) set an upper limit for the physical half-life for weathering of uranium and other radionuclides from soil at 100 years, although this value is based solely on concensus rather than on experimental data. Controlled experiments designed to measure uranium loss rates from cultivated soils treated with sludges should be carried out to provide an indication of the true weathering rate from surface soils before long-term application guidelines for uranium to soils are set.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions (Radiological Implications)

Based on this survey and evaluation, several conclusions can be drawn.

1. Uranium concentrations in Port Hope sewage sludges are considerably higher than concentrations measured in sludges from other region WPCPs, and averaged between 5.2 and 6.8 mg/L in fresh digested sludges. Previous studies have identified Eldorado Resources Limited (ERL) as the primary uranium source in Port Hope sewage.

2. Activity concentrations of U-238 decay products were slightly higher in Port Hope sludges than in sludges from other plants, but were lower than found in older Port Hope sewage sludges (approximately 40 m^3) stockpiled prior to closure of the old ERL UO_3 plant. The source(s) of these decay products have not been identified.

3. In soils from four farms having a prior history of fertilization with Port Hope sewage sludge at rates above the sludge utilization guideline, uranium concentrations ranged between 1.9 and 12.9 ppm, although only one sample showed concentrations above 3.1 ppm. Concentrations in control soils were 1.0 to 2.3 ppm, with the lowest concentrations occurring in woodlot soils where inorganic fertilizers have probably never been applied. Measured concentrations in treated fields could be roughly predicted based on records of sludge application rates. Differences between predicted and observed concentrations in some cases implied some weathering loss of the uranium added through sludge application.

4. Uranium and U-238 decay products were found at considerably lower concentrations in Port Hope sewage sludge than in typical inorganic phosphate fertilizers. However, typical application rates of radionuclides would be considerably higher for uranium and slightly higher for U-238 decay products in soils fertilized with Port Hope sewage sludge, due to the large volumes that would be applied. If Port Hope sludges were applied at the maximum rate

recommended by the provincial sludge utilization guidelines, concentrations in surface soil after five years would be 0.85 ppm for uranium and 0.1 to 0.4 $mBq \cdot g^{-1}$ for Th-230, Ra-226, Pb-210 and Po-210. These are less than typical background concentrations of about 2 ppm for natural uranium and 25 $mBq \cdot g^{-1}$ for members of the U-238 decay series.

5. Edible plant tissues generally had uranium concentrations that were below the 0.2 ppm dry weight detection limit, including tomatoes growing in undiluted Port Hope sludge. Leaves and stems had slightly higher uranium concentrations (up to 1.5 ppm dry weight), while roots typically showed the highest uranium concentrations (up to 4 ppm dry weight). The geometric mean soil-to-plant transfer coefficient for uranium was 0.0063 for all tissues (fresh weight plant-dry weight soil basis).

6. The effective dose equivalent to a hypothetical farmer due to fertilizing with Port Hope sewage sludge at the maximum rate prescribed by the sludge utilization guidelines is estimated at 0.00059 $mSv \cdot yr^{-1}$ for soils treated over five years, assuming intake through radionucide inhalation in dust and ingestion in crops, as well as exposure to gamma radiation from the airborne dust and the surface soil. The incremental dose received in a case where fields have been fertilized with sludge until soil uranium concentrations reach 10 ppm (after at least 50 years of sludge application) would be about 0.0056 $mSv \cdot yr^{-1}$. About 91% of the total dose is attributed to uranium, and the balance to Th-230 and its decay products. Most of the total dose is received through ingestion.

7. The effective dose equivalent received by the hypothetical farmer having soils at 10 ppm uranium (0.0056 $mSv \cdot yr^{-1}$) is slightly more than half of the annual dose limit designated as trivial by the International Atomic Energy Agency. This dose is only 0.3% of the average dose of 2 $mSv \cdot yr^{-1}$ received from natural background sources of radiation.

8. It is concluded that application of Port Hope sewage sludge on agricultural lands at the rates prescribed in the provincial sludge utilization guidelines would not result in significant human radiological impact.

7.2 Conclusions (Other Implications)

1. The dietary intake of uranium attributed to Port Hope sludge use through a heavy consumption of crops grown on sludge-amended fields is estimated at 210 $ug \cdot yr^{-1}$ for fields fertilized at the maximum prescribed rate for five years, and 2,000 $ug \cdot yr^{-1}$ for fields fertilized until soil uranium levels have reached 10 ppm. In comparison, the safe upper limit for uranium intake, as identified by Health and Welfare Canada, is about 25,000 $ug \cdot yr^{-1}$ based on chemical toxicity. On this basis, the application of Port Hope sewage sludge on agricultural lands at the rates prescribed in the provincial sludge utilization guidelines should not pose a chemical exposure hazard.

2. The maximum concentration of uranium in soils that should not elicit chemical toxic effects in crops is thought to be 10 ppm, based on a single study on wheat grown in soils treated with uranyl nitrate. The uranium in Port Hope sludge is probably less bioavailable and, therefore, less toxic than soluble uranyl nitrate; thus, a safe upper limit for uranium in sludge-treated soils may be greater than 10 ppm. About 50 years of regular application of sludge at the maximum prescribed rate would be required to bring soil uranium concentrations to 10 ppm, assuming no weathering losses.

3. Uranium would only accumulate to a safe upper limit for plant growth after about 50 years of sludge application, assuming no weathering loss of uranium from surface soil. This 50-year period is within the range of time periods required to reach maximum acceptable levels of other metals in soils treated with sludges at the designated concentration limits.

7.3 Recommendations

Since the radiation dose associated with the landspreading of Port Hope sewage sludges to the most highly exposed critical group would be below levels recognized by the national and international regulatory and scientific bodies as trivial, it is recommended that, unless new data different from that uncovered in this report become available, further studies on uranium in the Port Hope sludges focus on the more limiting area of phytotoxicology.

8.0 REFERENCES

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APPENDIX I

Historic Data on Radionuclides in Port Hope Sewage Sludges and Sludge-Amended Soils

TABLE A1.1: HISTORIC DATA ON URANIUM CONCENTRATIONS IN PORT HOPE SEWAGE SLUDGES

Sample Description	Dry Weight (ug/g)	Wet Weight (ug/g)	Comments
December 1986-January 1987:			
o Raw Sludge	152	5.55	ERL data - as reported by the Brown (1987); all values means of 9 determinations
	142	5.11	NAA data
	167	5.87	MOE data
o Aerobic Digest	232	4.42	ERL data
	235	4.47	NAA data
	209	3.98	MOE data
o Anaerobic Digest	212	6.58	ERL data
	216	6.48	NAA data
	309	9.27	MOE data
Aerobic Digest:			
28.01.86		3.25	MOE data
17.06.86		19.5	
16.09.86		2.5	
18.11.86		6.4	
09.12.86		0.96	
06.01.87		6.6	
02.02.87		5.4	
11.03.87		6.33	
24.03.87		4.16	
07.04.87		5.04	
21.04.87		5.65	
05.05.87		6.8	
19.05.87		4.72	
04.06.87		6.4	
Anaerobic Digest:			
30.10.85		10.5	
28.01.86		15.0	
17.06.86		6.75	
16.09.86		1.26	
18.11.86		6.93	
09.12.86		1.56	
06.01.87		14.5	
02.02.87		12.5	
11.03.87		10.13	
24.03.87		6.65	
07.04.87		9.11	
21.04.87		5.95	
05.05.87		9.05	
19.05.87		4.82	
04.06.87		6.1	
1981-82 Pile - Composites (dried sludges) 30.10.85	428 470		MOE data
1982-83 Pile - Composites (dried sludges) 30.10.85	440 410		
1984 Pile - Composites (dried sludges) 30.10.85	191 360		
21.04.86 (grabs)	440 460 480 470		
East Lawn Grab Samples 23.04.87 (dried sludges)	53.5 64.0		
Dried Sludges (undated)	396 432		
Cobourg Sludge (control)	L 0.1	L 0.005	

MOE - Ontario Ministry of the Environment.

NAA - Neutron activation analysis.

ERL - Eldorado Resources Ltd. analysis.

TABLE A1.2: ACTIVITIES* OF U-238 DECAY PRODUCTS IN PORT HOPE SEWAGE SLUDGES (MOE data)

Sample Description		Th-230	Ra-226	Pb-210	Po-210
Dried Sludge:	Initial sample (Bq/g)		1.5		
	Second sample (Bq/g)	0.45	0.17	0.45	0.30
Wet Digested Sludge			1.6±0.4		
Cobourg Wet Digested Sludge (control)			L 1.7		
Cobourg Dry Digested Sludge			0.006±0.001		
1981-82 Pile - 30.10.85 (Bq/g)			0.065		
(Composites)			0.038		
1982-83 Pile - 30.10.85 (Bq/g)			0.050		
(Composites)			0.070		
1984 Pile - 30.10.85 (Bq/g)			0.029		
(Composites)			0.046		
21.04.86 (grabs) (Bq/g)			0.30		
			0.32		
			0.18		
			0.22		
Wet Sludges:	31.10.85 (anaerobic)		1.6		
	13.01.86 (anaerobic)		2.1		
	28.01.86 (aerobic)		1.4		

* Bq/L unless indicated otherwise.

TABLE A1.3: SUMMARY OF RECORDS OF PORT HOPE SLUDGE APPLICATION ON AREA FARMLAND, AND LEVELS OF URANIUM AND Ra-226 IN SURFACE SOILS, BASED ON SAMPLING IN 1986 AND 1987. Data as provided by the Ministry of the Environment, Peterborough District Office.

Farm No.	Volume Applied (total) (m^3)	Field No.	Volume per Field (m^3)	Area (ha)	Time of Application	Measured Concentrations U (ppm)	Measured Concentrations Ra-226 (mBq/g)	Predicted Incremental Concentration of Uranium[1] ppm
1	U	1	U	20	1970-74	2.9	31	-
2	407	1	U	0.8	1983	1.9	[illegible]	[illegible]
		2	U	4		2.0	[illegible]	
3	4,130	1	U	14	1977, 78	3.2	[illegible]	[illegible]
		2	U	4		2.0	[illegible]	
4	259	1	259	8	1982	L 1.9	23	[illegible]
5	990	1	U	0.4	1979, 80	2.2	[illegible]	-
		Control	U	1.6		L 1.9	[illegible]	
6	4,760	1	4,760	4	1977-79	2.6	24	[illegible]
		1 (subsection)				8.8	26	average
7	6,710	1	U	10		2.0	21	[illegible]
		2	U	2	1978, 79, 81	L 1.9	21	
		3	U	4.9		L 1.9	23	
8	Did not receive sludge, no data.							
9	1,990	1	1,990	U	1980	4.0	21	-
10	545	1	U	6	1977	1.9	24	[illegible]
		2	U	6		2.2	23	
		3	U	8		4.0	23	
11	345	1	345	2.4	1978	2.5	22	[illegible]
12	749	1	749	8	1982	not sampled		
13	681	1	U	4	1980, 81	1.9	25	[illegible]
		2	U	6		2.2	25	
14	4,760	1	U	4	1977-79	2.9	14/23	[illegible]
						3.4*		
		2	U	1.6		1.9	23	
15	1,450	1	1,450	2.8	1977	4.6	26/23	[illegible]
		Control				3.7*		
						1.9*	23	
16	1,540	1	U	4.9	1980	2.7	[illegible]	[illegible]
		2	U	1.2		2.9	[illegible]	
17	340	1	340	8	1978	2.5	31	[illegible]
18	7,770	1	U	U	1976,77,80,81	not sampled		
		2						
		3						
		4						
19	2,910	1	U	10	1984, 85	L 2.4	17	[illegible]
		3	U	19		L 2.4	8	
20	Did not receive sludge, no data.							
21	9,170	1	U	10	1982-84	L 2.4	[illegible]	[illegible]
		2	U	2		21.6	19/26	
						13.6*		
		3	U	1.6		10.4	22	
		4	U	4.9		3.84	22	
22	844	1	U	8.1	1983	2.1	26	[illegible]
		2	U	0.4		1.9	23	
23	395	1	U	U	1985	L 2.4	17	-
24	363	1	363	16	1978	L 1.9	23	[illegible]
25	42	not sampled						
26	2,680	1	U	20	1978, 79, 81	2.6	22	[illegible]
		2	U	6.1		1.9	22	

[1] Our calculations: predicted uranium concentration added, based on reported volumes applied and areas fertilized. Uranium concentation assumed to average 6 ppm in sludge. Assumed plough depth = 15 cm; assumed soil bulk density = 1.6 g/cm^3. Averages for all fields if individual field application rates unspecified.

* Split samples also analyzed by Atomic Energy of Canada Limited for the present study.

U - unknown.

TABLE A1.4: URANIUM CONCENTRATION (ppm) IN EDIBLE HERBS AND SOIL IN A GARDEN AMENDED WITH DRIED PORT HOPE SEWAGE SLUDGE (McLaughlin, 1986)

Species	Sample Type and Location	Uranium[1]
French Sorrel	foliage[2]	0.21
	soil[3]	15.0
Lemon Balm	foliage	0.34
	foliage (Control[4])	0.02
	soil	2.30
Sweet Cicily	foliage	0.10
	soil	7.1
Lovage	foliage	0.11
	foliage (Control)	0.05
	soil	6.59
Garlic Chive	foliage	0.08
	foliage (Control)	0.02
	soil	11.0
Catnip	foliage	0.32
	soil	23.0

[1] Parts per million, mean of duplicate samplings, dry weight.

[2] Current year's foliage.

[3] To 10 cm depth, directly adjacent to plant.

[4] Collected from similar outdoor garden, without sewage soil addition.

APPENDIX 2

Raw Data Tabulations

TABLE A2.1: RAW DATA, ANALYSES OF INDIVIDUAL SLUDGE SAMPLES

	Solids (%)	(NH_4-N (mg/L)	NO_3-N (mg/L)	U (ug/g solids)	U (ug/L sludge)
30 July					
Anaerobic Digest	3.8	360	0.6	155	5,890
Anaerobic Raw	2.9	164	L 0.1	150	4,350
Aerobic Digest	2.8			195	5,460
Aerobic Waste	0.7			135	945
Pringle Creek	2.5			4.1	103
Corbett Creek	7.1			3.5	249
Cobourg-West	1.7			3.0	51
08 August					
Anaerobic Digest	3.3	410/400	L 0.1	175	5,775
Anaerobic Raw	2.6	144/144	L 0.1	195	5,070
Aerobic Digest	2.8			185	5,180
Aerobic Waste	0.6			235	1,410
81/82 Pile	68.2			470	-
83/84 Pile	67.5			250	-
85 Pile	62.4			520	-
85/86 Pile	79.2			58/61	-
October 86 Drying Bed	11.6			230	-
1987 Drying Bed	30.0			145	-
Pringle Creek	2.5			5.2	130
Corbett Creek	3.5			L 0.2	L 7
Cobourg-West	2.0			2.2	44
Port Darlington	2.5			3.2	80
26 August					
Anaerobic Digest	3.3			205	6,765
Anaerobic Raw	3.4			185	6,290
Aerobic Digest	2.9	0.23	66	225/230	6,600
Aerobic Waste	0.7			205	1,435
Pringle Creek	3.1			4.4	136
Corbett Creek	3.2			3.0	96
Cobourg-West	1.7			2.0	34
Port Darlington	3.5			L 0.2	L 7

TABLE A2.2: RAW DATA: ANALYSIS OF COMPOSITE* SLUDGE AND SOIL SAMPLES

	Loss on Ignition (% of total solids)	Th-230 (Bq/g)	Ra-226 (Bq/g)	Pb-210 (Bq/g)	Po-210 (Bq/g)
Anaerobic Digest	47.4	0.026±0.008	0.017±0.005	L 0.1	0.080±0.010
Anaerobic Raw	58.8				
Aerobic Digest	46.5	0.058±0.010	0.047±0.009	L 0.1	0.100±0.010
Aerobic Waste	52.9				
81/82 Pile	18.0	0.17±0.05	0.40±0.03	0.42±0.04	0.58±0.02
83/84 Pile	24.6				
85 Pile	28.2				
85/86 Pile	10.9				
Oct 86 Drying Bed	47.1	0.031±0.006	0.053±0.007	L 0.1	0.082±0.010
1987 Drying Bed	42.0				
Pringle Creek	51.7				
Corbett Creek	47.2	0.010±0.004	0.015±0.003	L 0.1	0.022±0.005
Cobourg - West	62.0/62.0	L 0.005	L 0.005	L 0.1	0.025±0.005
Port Darlington	50.1				
Farm 21 Soil (mid-south/ far south composite)		0.016±0.007	0.021±0.004	L 0.1	0.056±0.007
Blind Standard (UTS-2)		4.0±0.3	5.3±0.3	3.8±0.4	4.2±0.1
(Duplicate Results)		4.5±0.3	5.1±0.3	-	-
UTS-2 Consensus Value		4.4	5.6	3.25	3.1
UTS-1		3.4±0.3	3.5±0.2	2.8±0.3	3.1±0.1
UTS-1 Consensus Value		3.6	3.67	3.25	3.1

* Sludge samples composite of three samples per STP, except for Port Darlington (two samples).

TABLE A2.3: CONCENTRATIONS OF VARIOUS ELEMENTS IN SELECTED SEWAGE SLUDGES AND SOIL (concentrations are ppm dry weight)

	Composite Anaerobic Digest	Composite Aerobic Digest	Composite Corbett Creek	Composite Cobourg	Farm 21 Soil Far + Mid South
Be	2	2	1	L 1/L 2	1/1
Mo	4	5	5	11/10	2/2
Ca	27,000	21,000	24,000	17,200/14,900	9,600/10,800
V	14	16	15	6/6	46/45
Al	33,000	34,000	37,000	1,710/1,760	16,500/16,800
Mg	2,700	2,700	2,400	4,900/4,900	4,400/4,500
Ba	640	860	440	220/220	77/79
K	1,570	1,970	1,770	4,300/4,300	2,200/2,300
Sr	148	149	143	72/72	25/27
Na	2,100	2,400	2,100	4,000/4,100	730/770
Zn	520	620	1,150	4,800/4,800	76/76
Cd	4.5	5.5	25	2.5/3.0	0.24/0.28
Mn	220	230	168	270/260	490/490
Co	6	6	6	7/7	8/7
Cu	390	550	3,100	270/250	28/24
Fe	6,800	8,100	15,800	38,000/37,000	22,000/21,000
Pb	117	146	360	1,930/2,000	17/15
Cr	75	87	1,720	610/590	28/28
Ni	45	108	740	184/177	15/14

Note: Sludge composites consist of mixtures from three sampling events.

APPENDIX 3

Dose Conversion Factors and Soil-to-Plant Transfer Factors for Modelling Radiation Exposure to Radionuclides in Sludge-Amended Soils

A3.1 Derivation of Dose Conversion Factor for External Exposure to Natural Uranium and U-238 Decay Chain Radionuclides from a 15-cm Thick Slab Source

Once sewage sludge is ploughed into the surface soil, radionuclides in the sludge may be assumed to be uniformly distributed throughout the plough depth (15 cm). Gamma radiation ("groundshine") given off by these nuclides will constitute an external exposure pathway to individuals working on the sludge-amended soils.

Natural uranium consists of 99.275 atom percent of U-238 in secular equilibrium with U-234 (0.0054 atom percent), plus 0.72 atom percent of U-235. Essentially, all the long-lived, non-uranium daughters have been removed from the yellowcake processed by ERL, and only the relatively short-lived daughters will grow back in within a reasonable period of time. Examination of the decay schemes of U-238 and U-235 (see Figure A3.1) shows that only U-238, Th-234, Pa-234m, Pa-234, U-234, U-235 and Th-231 need to be considered in dosimetric calculations. The long-lived Th-230 in the U-238 series, and Pa-231 in the U-235 series, will not be grown in within a reasonable time; the decay chains are effectively terminated at U-234 and at Th-231 in the two series, respectively, for this application.

U-235 is present in natural uranium at 0.72 atom percent. Its radioactivity expressed as a fraction of the radioactivity of U-238 is equal to:

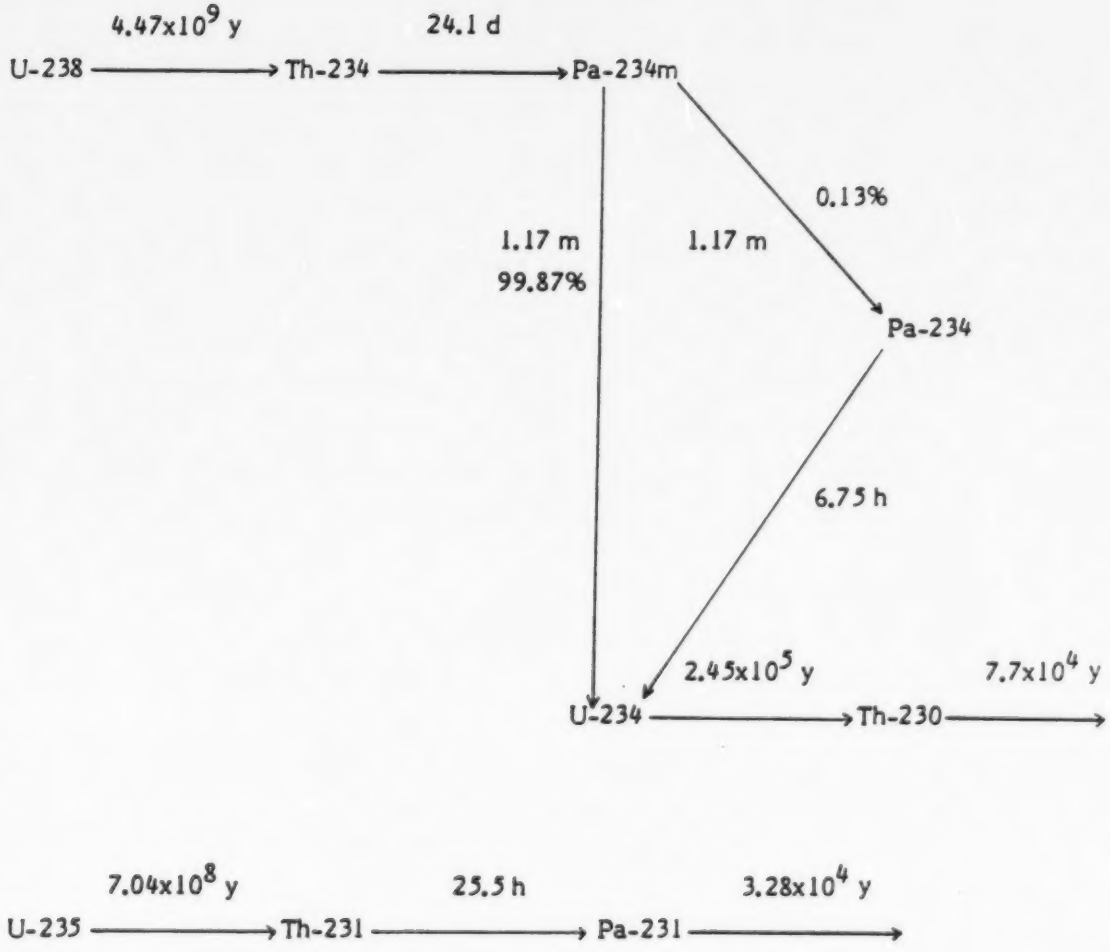
$$0.0072 \times \frac{4.47 \times 10^{9}}{7.04 \times 10^{8}} = 0.046$$

where the ratio is the half-life of U-238, in years, relative to that of U-235.

The contents of radionuclides associated with 1 Bq of U-238 in chemically refined natural uranium are given below:

Radionuclide	Content (Bq)
U-238	1
Th-234	1
Pa-234m	1

FIGURE A3.1: RADIONUCLIDE DECAY SCHEMES AND HALF-LIVES



Pa-234	0.0013
U-234	1
U-235	0.046
Th-231	0.046

The external dose conversion factors, in Gy/a per Bq/cc, in air above uniformly contaminated soil of various thicknesses have been calculated by Kocher and Sjoreen (1985). Values plotted as a function of gamma energy for 15-cm thick soil are given in Figure A3.2. Using these data and radionuclide decay data given in Kocher (1981), external dose conversion factors for all the radionuclides of interest are calculated and given in Table A3.1. Using the relative contents of the various radionuclides given above, the dose rate in air above a 15-cm thick soil layer uniformly contaminated with natural uranium at a concentration of 1 Bq/cc of U-238 is calculated as shown in Table A3.2. Its value is 2.57×10^{-5} Gy/a per Bq/cc U-238.

The ratio of the whole body effective dose (Sv) to air dose (Gy) has been calculated for various gamma energies (CEC, 1979). It may be shown that, over the gamma energy range of 0.05 to 2 MeV, an average Sv/Gy ratio of 0.8 is appropriate. Hence, the effective dose rate factor for the above exposure situation is:

$$2.57 \times 10^{-5} \times 0.8 = 2.06 \times 10^{-5} \text{ Sv/a per Bq/cc}$$

While U-234 decay products do occur in Port Hope sludges at activity concentrations that tend to exceed those in other sewage sludges, their sources have not been identified. These radionuclides may contribute incrementally to radionuclide loadings to soil relative to normal rates that occur routinely from inorganic fertilizer use. External dose conversion factors, calculated in the same manner as described above for natural uranium, are derived in Table A3.3. At secular equilibrium, the relative activity abundances of all nuclides given in Table A3.3 is the same as the activity abundance of its parent. The effective dose rate conversion factors from Table A3.3 ($Sv \cdot yr^{-1}$ per $Bq \cdot cm^{-3}$) are:

Th-230	1.3×10^{-7}
Ra-226 (including radon and daughters)	1.9×10^{-3}
Pb-210	3.8×10^{-7}

FIGURE A3.2

GAMMA DOSE RATE FACTOR (Gy/yr PER Bq/cm^3)IN AIR FOR UNIFORM SLAB SOURCE OF 15-CM THICK SOIL
(from Kocher and Sjoreen, 1985)

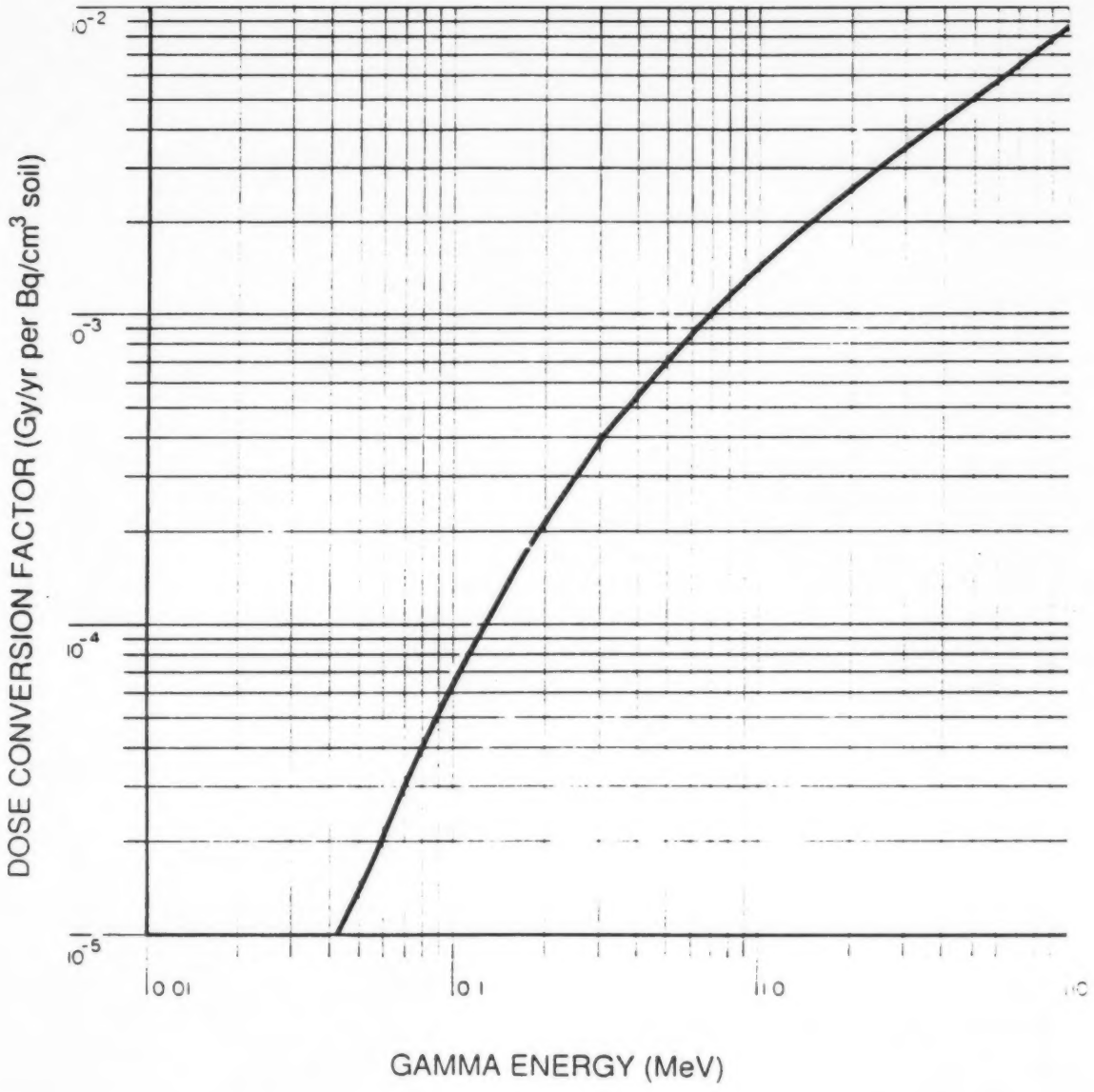


TABLE A3.1: EXTERNAL DOSE CONVERSION FACTOR CALCULATIONS FOR A UNIFORMLY CONTAMINATED 15-cm THICK SLAB OF SOIL

Nuclide	Gamma Energy (MeV)	Fractional Abundance (f)	Dose Conversion Factor (DCF) (Gy/a per Bq/cc)	f x DCF (Gy/a per Bq/cc)
U-238	0.013	0.088	0.00E+00	0.00E+00
Th-234	0.06329	0.038	2.30E-05	8.74E-07
	0.09238	0.0272	5.70E-05	1.55E-06
	0.0928	0.0269	5.80E-05	1.56E-06
	0.1128	0.00242	9.00E-05	2.18E-07
				4.20E-06
Pa-234m (1.17 m)	0.0947	0.00115	6.00E-05	6.90E-08
	0.0984	0.00187	6.50E-05	1.22E-07
	0.7664	0.00207	1.10E-03	2.28E-06
	1.001	0.00589	1.40E-03	8.25E-06
				1.07E-05
U-234	0.0532	0.00118	1.55E-05	1.83E-08
U-235	0.0727	0.001	3.25E-05	3.25E-08
	0.08995	0.027	5.40E-05	1.46E-06
	0.09335	0.045	5.90E-05	2.65E-06
	0.105	0.021	7.70E-05	1.62E-06
	0.1091	0.015	8.20E-05	1.23E-06
	0.12	0.0015	1.00E-04	1.50E-07
	0.1408	0.0022	1.32E-04	2.90E-07
	0.1438	0.105	1.37E04	1.44E-05
	0.1634	0.047	1.70E-04	7.99E-06
	0.183	0.544	2.02E-04	1.10E-04
	0.195	0.0059	2.15E-04	1.27E-06
	0.202	0.01	2.26E-04	2.26E-06
	0.2053	0.047	2.35E-04	1.10E-05
	0.2214	0.001	2.60E-04	2.60E-07
				1.55E-04
Th-231	0.05857	0.0048	1.94E-05	9.31E-08
	0.07278	0.00248	3.20E-05	7.94E-08
	0.08124	0.0088	4.20E-05	3.70E-07
	0.08211	0.004	4.40E-05	1.76E-07
	0.08421	0.064	4.60E-05	2.94E-06
	0.08995	0.0093	5.40E-05	5.02E-07
	0.09229	0.0035	5.70E-05	2.00E-07
	0.09587	0.0057	6.40E-05	3.65E-07

TABLE A3.1: EXTERNAL DOSE CONVERSION FACTOR CALCULATIONS FOR A UNIFORMLY CONTAMINATED 15-cm THICK SLAB OF SOIL

Nuclide	Gamma Energy (MeV)	Fractional Abundance (f)	Dose Conversion Factor (DCF) (Gy/a per Bq/cc)	f x DCF (Gy/a per Bq/cc)
	0.1	0.00529	6.80E-05	3.60E-07
	0.108	0.0026	8.00E-05	2.08E-07
	0.1631	0.00153	1.70E-04	2.60E-07
				5.56E-06
Pa-234 (6.75 h)	0.07	0.036	2.90E-05	1.04E-06
	0.098	0.461	6.50E-05	3.00E-05
	0.125	0.332	1.10E-04	3.65E-05
	0.14	0.0165	1.30E-04	2.14E-06
	0.153	0.0771	1.55E-04	1.20E-05
	0.172	0.0071	1.81E-04	1.29E-06
	0.19	0.031	2.10E-04	6.51E-06
	0.21	0.0252	2.40E-04	6.05E-06
	0.227	0.116	2.65E-04	3.07E-05
	0.248	0.0382	3.00E-04	1.15E-05
	0.27	0.0144	3.40E-04	4.90E-06
	0.29	0.0426	3.80E-04	1.62E-05
	0.32	0.0156	4.30E-04	6.71E-06
	0.36	0.0494	5.00E-04	2.47E-05
	0.43	0.0332	6.10E-04	2.03E-05
	0.485	0.0315	7.00E-04	2.21E-05
	0.55	0.085	7.90E-04	6.72E-05
	0.57	0.13	8.10E-04	1.05E-04
	0.615	0.056	8.90E-04	4.98E-05
	0.68	0.173	9.70E-04	1.68E-04
	0.76	0.234	1.10E-03	2.57E-04
	0.84	0.176	1.20E-03	2.11E-04
	0.89	0.345	1.24E-03	4.28E-04
	0.926	0.232	1.30E-03	3.02E-04
	0.948	0.202	1.32E-03	2.67E-04
	0.97	0.021	1.36E-03	2.86E-05
	0.982	0.069	1.36E-03	9.38E-05
	1.05	0.0291	1.45E-03	4.22E-05
	1.15	0.0249	1.55E-03	3.86E-05
	1.25	0.0229	1.70E-03	3.89E-05
	1.36	0.0182	1.80E-03	3.28E-05
	1.4	0.0353	1.85E-03	6.53E-05
	1.5	0.0346	1.95E-03	6.75E-05
	1.7	0.0466	2.15E-03	1.00E-04
	1.9	0.0114	2.36E-03	2.69E-05
				2.62E-03

TABLE A3.2: EXTERNAL DOSE RATE FACTOR IN AIR FOR NATURAL URANIUM DISTRIBUTED UNIFORMLY IN THE SURFACE 15 cm OF SOIL ($Gy \cdot yr^{-1}$ per $Bq \cdot cm^{-3}$ U-238)

Nuclide	Concentration (C) (Bq/cc soil)	Dose Conversion Factor (DCF) (Gy/a per Bq/cc)	C x DCF (Gy/a per Bq/cc)
U-238	1	0	0
Th-234	1	4.20E-06	4.20E-06
Pa-234m	1	1.07E-05	1.07E-05
Pa-234	0.0013	2.62E-03	3.41E-06
U-234	1	1.83E-08	1.83E-08
U-235	0.046	1.55E-04	7.13E-06
Th-231	0.046	5.56E-06	2.56E-07
			2.57E-05

TABLE A3.3: DERIVATION OF EFFECTIVE DOSE RATE CONVERSION FACTORS FOR Th-230 AND ITS DECAY PRODUCTS FOR EXPOSURE TO A 15-cm THICK SLAB SOURCE

Nuclide	Gamma Energy (Mev)	Fractional Abundance	Dose Conversion Factor (Gy/a per Bq/cc)[1]	f x DCF (Gy/a per Bq/cc)	Effective Dose DCF (Sv/a per Bq/cc)
Th-230	0.068	0.0037	2.8E-5	1.04E-7	
	0.144	0.00045	1.4E-4	6.30E-8	
				1.67E-7	1.3E-7
Ra-226	0.186	0.033	2.1E-4	6.93E-6	
Rn-222	0.51	0.0007	7.5E-4	5.25E-7	
Pb-214	0.25	0.084	3.1E-4	2.60E-5	
	0.295	0.19	3.8E-4	7.22E-5	
	0.352	0.37	4.9E-4	1.81E-4	
				2.79E-4	
Bi-214	0.609	0.46	8.7E-4	4.00E-4	
	0.66	0.017	9.4E-4	1.60E-5	
	0.77	0.053	1.1E-3	5.83E-5	
	0.81	0.013	1.2E-3	1.56E-5	
	1.12	0.017	1.5E-3	2.55E-5	
	1.24	0.075	1.7E-3	1.28E-4	
	1.4	0.13	1.9E-3	2.47E-4	
	1.66	0.012	2.1E-3	2.52E-5	
	1.73	0.03	2.2E-3	6.60E-5	
	1.76	0.16	2.2E-3	3.52E-4	
	1.9	0.03	2.4E-3	7.20E-5	
	2.2	0.066	2.7E-3	1.78E-4	
				1.58E-3	
Po-214	0.8	0.0001	1.1E-3	1.1E-7	1.9E-7
Pb-210	0.047	0.04	1.2E-5	4.8E-7	3.8E-7
Po-210	0.803	0.000011	1.1E-3	1.2E-8	9.7E-9

[1] From Figure A3.2.

A3.2 Internal Exposure, Cloud Immersion and Plant Uptake

Dose conversion factors for natural uranium and U-238 decay chain radionuclides are summarized in Lush et al. (1985) for ingestion, inhalation and immersion in an airborne "cloud" of radionuclides, based on values given by Johnson and Dunford (1983) and Kocher (1983). The dose conversion factor for ingestion of Th-230 is based on the revised value given by Johnson (1986). These values are summarized in Table A3.4.

Soil-to-plant uptake factors (B_v) for Th, Ra, Pb and Po are taken from Letourneau (1987), while the B_v for uranium is based on plant and soil uranium concentrations measured in this study. Units are ug or Bq per gram fresh weight of plant tissue divided by ug or Bq per gram dry weight of surface soil. B_v values used in this assessment are given in Table A3.4.

TABLE A3.4: DOSE CONVERSION FACTORS FOR INHALATION (inh), INGESTION (ing), CLOUD IMMERSION (a) AND SOIL-TO-PLANT UPTAKE FACTORS FOR NATURAL URANIUM AND U-238 DECAY CHAIN RADIONUCLIDES[1]

	DCF_{inh} ($Sv \cdot Bq^{-1}$)	DCF_{ing} ($Sv \cdot Bq^{-1}$)	DCF_a ($Sv \cdot yr^{-1}$ per $Bq \cdot m^{-3}$)	B_v
U-nat[2]	1.0×10^{-6}	2.0×10^{-9}	4.64×10^{-10}	6.3×10^{-3}**
Th-230	8.1×10^{-5}	3.5×10^{-6}*	5.29×10^{-10}	5.0×10^{-4}
Ra-226	2.6×10^{-6}	3.2×10^{-7}	9.26E-9	5.0×10^{-3}
Pb-210	3.5×10^{-6}	1.6×10^{-6}	1.81×10^{-9}	1.0×10^{-3}
Po-210	2.5×10^{-6}	5.3×10^{-7}	1.19×10^{-11}	2.0×10^{-4}

1 Dose conversion factors and B_v values are given by Lush et al. (1985), unless otherwise indicated.

2 Natural uranium values expressed on a mass (microgram) rather than on an activity basis (i.e., $Sv \cdot ug^{-1}$ or $Sv \cdot yr^{-1}$ per $ug \cdot m^{-3}$). U-nat is 99.275 atom % U-238 (contributions from Th-234 and Pa-234m included), 0.0054 atom % of U-234, and 0.72 atom % of U-235 (contributions from Th-231 included).

* Value as recently revised by J.R. Johnson, Chalk River Nuclear Laboratories.

** Uranium B_v value based on uptake factors measured in this study.